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Does obesity affect foot structure and function, foot sensation and plantar pressure in children?

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Does obesity affect foot structure and function, foot sensation and plantar pressure distribution in children?

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Declaration

I declare that the work presented in this thesis is original work and has not been submitted for any other academic qualification at this or any institution. The Department of Biomedical Science, University of Wollongong, holds copies of the original data analysed within this thesis.

Annaliese M. Dowling

Dedication

To Mum, Dad, Edwina, Dave and Kate,
who have been involved from the beginning.
Thank you for all for your love, support and encouragement.
To Tim, who has been my pillar of strength throughout this thesis.

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- Jessica Steele who helped pilot my protocols for the study.

Abstract

Childhood obesity is considered to be reaching epidemic proportions where obese children tend to become obese adults. As obese individuals have increased mass they are at greater risk of developing musculoskeletal dysfunction, which may in turn alter quality of life. One main musculoskeletal concern is the feet of obese individuals, as the feet are the foundation for stance and gait. Musculoskeletal foot pathologies have not been widely investigated in relation to childhood obesity. However, previous research has found a general trend for obese children to have flatfeet and generate higher pressures under the forefoot during gait. These high pressures in the forefoot region have potentially serious negative consequences and urgently need to be further investigated. At present, it is unknown to what extent these flatfeet and higher pressures in the forefoot region can alter foot function. Therefore, the purpose of this study was to assess foot structure and function, foot sensation and plantar pressure distributions in both an obese and non-obese sample of children aged 6 to 12 years.

Sixty-five consenting 6 to 12 year olds participated in the assessment of foot structure, function, sensation and plantar pressure. Of the sample tested, 10 children classified as obese according to BMI for age and gender criteria and 10 non-obese children matched for age, height and gender participated as subjects. A pedograph was used to characterise shape of the plantar surface whereas 26 anthropometric foot measurements per limb were undertaken to assess foot dimensions and foot shape. The foot sensations of pressure and vibration were then assessed on the plantar surface of the subject's feet. Static and dynamic rearfoot alignment and rearfoot motion were recorded in two-dimensions using a video camera while plantar pressures were recorded using the Novel AT-4 system® (25 Hz). After processing, pedograph, anthropometry, sensation, rearfoot alignment, motion, and plantar pressure data were analysed using appropriate statistics to determine the effects of obesity on the dependent variables.

An effect of obesity was found on the pedograph and foot anthropometry data whereby the obese children displayed greater foot contact area and larger, broader and thicker feet. However, there was no effect of obesity on foot sensations detected on the plantar surface of the foot, the rearfoot alignment or the rearfoot motion data, although rearfoot

alignment was affected in children by the distance the heels were apart from each other. In both the static and dynamic trials the obese subjects generated significantly greater forces over a significantly larger foot contact area, although this increased area was not sufficient to moderate the plantar pressure values. That is, the obese children generated significantly higher static and dynamic plantar pressures in the midfoot area and under the second to fifth metatarsal heads compared to the non-obese counterparts, despite an increased contact area. Additionally, obese children generated significantly greater force-time and pressure-time integrals compared to the non-obese children. Therefore, it was postulated that obese children were at risk of developing foot pathologies particularly in the forefoot region.

It was concluded that, although obesity appears to have no effect on plantar sensations or static rearfoot alignment, structurally, the feet of the obese child are broader, higher and thicker than the feet of the non-obese children. In addition, the long-term bearing of excessive mass by young children, caused by obesity appears to flatten the medial midfoot region, increasing the area and time this region of the foot contacts the ground. Functionally, obese children generated higher dynamic pressures and pressure-time integrals under the 2nd to 5th metatarsal heads when walking and thereby may be at an increased risk of developing foot pathologies or foot discomfort in this area of the foot. As the long-term consequences of these increased dynamic pressures are unknown for obese children, it is recommended that the feasibility of developing footwear specific to the unique structural and functional characteristics of the obese child's foot be investigated. The development of a shoe specifically for this population should be based on the unique characteristic features of obese children's foot shape, their increased foot contact area and the need for adequate forefoot cushioning to help decrease the pressures generated under the 2nd to 5th metatarsal heads. Development of footwear with these specific characteristics would ensure that obese children may comfortably participate in physical activities and, in turn, halt the cycle of obesity. This is urgently warranted as obesity in children is increasing throughout the world.

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Chapter 1

The Problem

1.0 Introduction

Obesity is a worldwide problem that can be defined as an excess accumulation of fat in the body. More specifically, it involves an abnormal increase in the proportion of fat cells, which are distributed both subcutaneously and in the viscera (Glanze, 1990). The proportion of people who have been classified as obese has increased over the last two decades both in Australia and throughout the world. For example, in 1989 a study conducted by the National Heart Foundation found that of the Australian population, 48% of men and 34% of women were overweight or obese (Bennett & Magnus, 1994). By 1995, a National Nutrition Survey revealed that the levels of overweight and obese Australians had risen in both men and women to 64% and 49%, respectively, since the 1989 study (ABS, 1995 cited in Donath, 2000).

There is unequivocal evidence that the incidence of childhood obesity is also increasing (see Section 2.0; Schonfeld-Warden & Warden, 1997; Lazarus *et al.*, 2000) such that in Australia 19.3 to 21.1% of boys are either overweight or obese and 21.3 to 23.5% girls are overweight or obese (Booth *et al.*, 2000). As obese children tend to become obese adults this epidemic in childhood obesity is a major concern*. This is compounded by the fact that the severity and age of the onset of obesity are significant determinants of whether obesity in childhood will progress into adulthood; the greater the severity of obesity in childhood, the greater the tendency to persist (Dietz, 1999). Furthermore, many complications of childhood obesity develop during childhood but the consequences do not become apparent until decades later (Must & Strauss, 1999).

This increasing prevalence of obesity in society is of significant concern as there are numerous long-term debilitating effects of obesity which may impair quality of life. For example, there is a secular trend that obese individuals are at a higher risk of

* Abraham *et al.*, 1960; Fisch *et al.*, 1975; NIH Statement, 1985; Rolland-Cachera *et al.*, 1987; Must *et al.*, 1992; Dietz, 1993; Mellin, 1993; Guo *et al.*, 1994; Epstein, 1995; Lazarus *et al.*, 1995; Schonfeld-Warden & Warden, 1997; Whitaker *et al.*, 1997.

cardiovascular disease, circulatory difficulties, diabetes mellitus (Type II) and various musculoskeletal disorders (James, 1995; Must & Strauss, 1999). Of these musculoskeletal disorders, a major problem suffered by obese adults is foot pathologies and/or foot pain. Poor foot mechanics can be a significant health problem as they may restrict the ability of an individual to participate in activities of daily life (Messier *et al.*, 1994). Complications of obesity, such as foot neuropathies in Type II diabetes patients, also contribute to the numerous foot disorders suffered by obese individuals.

The foot is an important structure as it is the foundation block for generating propulsive forces in gait as well as acting as the body's base of support which must endure both static and dynamic loads generated during all activities of daily living (Morris, 1977). Any change in structure or function of the foot, as may occur with foot pathologies, will influence functioning of the entire lower extremity which may, in turn, alter whole body movement patterns (Katoh *et al.*, 1983). Over time biomechanical dysfunction of the lower extremity can inhibit mobility, threatening independence and quality of life of the individual concerned.

One common foot pathology, which can influence lower extremity function, is *pes planus*, commonly termed 'flatfeet'. Foot discomfort and pain in flatfeet is apparent in varying degrees. Children, in the first few years of life, appear to walk with flatfeet. This is due to immature development of their feet, development of a fat pad in the midfoot area and their gait pattern. Therefore, this early flatfootedness does not cause any discomfort but rather enhances their balance and aids their ability to move due to an increased surface area of the foot in contact with the ground. As weight is gained with age, the tensile strength of the ligamentous and muscular structures of the child's foot increases. By about the age of 6 years a child has developed an adult foot structure with a fully formed longitudinal arch (Beauchamp, 1987; Norkin & Levangie, 1992; Debrunner, 1965 cited in Hennig *et al.*, 1994) and should therefore no longer display evidence of flatfeet. However, if flatfeet continues with age and weight gain, it may lead to problematic feet in later life. The long-term effects of flatfeet have not been fully established, although it is believed that flatfooted individuals can develop debilitating lower limb musculoskeletal problems if the pathology is severe and is not treated (Messier *et al.*, 1994).

Riddiford-Harland *et al.* (2000) examined the relationship between obesity and functional capacity in prepubescent children, finding a significant relationship between foot structure and obesity, whereby there was a trend for obese children to have flatfeet. That is, from static weight bearing footprints, Footprint Angles (FA)* calculated for the obese children were significantly less ($p < 0.001$) compared to their non-obese counterparts. Furthermore, the Chippaux-Smirak Index (CSI) was found to be significantly greater ($p < 0.001$) for the obese children. A decreased FA and an increased CSI have been associated with a lower longitudinal arch of the foot, a flatter cavity and a broader midfoot area of the footprint (Forriol & Pascual, 1990; Cavanagh & Rodgers, 1987). A decrease in the integrity or stability of the foot in weight bearing has also been associated with lowered arches (Forriol & Pascual, 1990). Based on their findings, it was suggested by Riddiford-Harland *et al.* (2000) that obese children as young as 8 years of age displayed functional characteristics in their feet which may develop into problematic symptoms in later life, particularly if their excessive weight gain continued. However, the authors acknowledged that further research was required to determine whether the structural changes they noted in the foot of the obese children in fact influenced actual foot function or were merely 'cosmetic' in nature.

Following the recommendation of Riddiford-Harland *et al.* (2000), Dowling *et al.* (2001) re-examined the effect of obesity on foot structure. However, the scope of the study was expanded to include assessment of the effects of obesity on plantar pressure distributions generated during standing and walking, both when the children were unloaded and when loaded with an additional 20% of their body mass. After replicating the FA and CSI findings of Riddiford-Harland *et al.* (2000), Dowling *et al.* (2001) also found that total foot peak force and peak area values generated by the obese children when standing were significantly greater ($p < 0.001$) to those generated by the non-obese children. That is, the obese children generated greater forces when standing but these were distributed over a greater area of the foot, thereby resulting in similar static plantar pressures to the non-obese children. Although these trends were also found for dynamic values of peak force and peak area for the total foot (T), and rearfoot (RF), it was evident that during dynamic gait obese children experienced significantly greater pressure ($p = 0.006$) in the forefoot region of the foot. This finding has potentially

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* The concepts of Footprint Angle and Chippaux Smirak Index are explained in Section 3.2.2.

negative repercussions for obese children as increased pressures exerted over the small bones and ligaments in the forefoot may cause forefoot injury in obese children. Furthermore, it was postulated that this increased forefoot pressure could cause foot discomfort during weight bearing activity, thereby acting as a deterrent to these children being physically active. Analysis of the loaded and unloaded plantar pressure results indicated that these changes in forefoot pressure were a consequence of the long-term excess weight bearing imposed on the children by their obesity rather than a temporary loading effect (see Section 2.3).

Despite the original contribution to our understanding of the effects of obesity on foot structure in children by the studies of Riddiford-Harland *et al.* (2000) and Dowling *et al.* (2001), there are still many questions pertaining to the effects of obesity on the structure and function of children's feet that remain unanswered. For example, apart from having flatter feet, does the shape of obese children's feet differ compared to their leaner counterparts? Do obese children experience any decrement in foot sensation as a consequence of their long-term excess weight bearing? Does foot function of obese children during activities such as walking differ relative to non-obese children? In order to address these unanswered questions, further research is urgently required in order to understand the effects of obesity on the feet of children, so that appropriate interventions can be implemented where required.

1.1 Statement of the Problem

The purpose of the present study was to investigate the effects of obesity on foot structure and sensation, foot function, and static and dynamic plantar pressure distributions in children.

1.2 Significance of the Study

Research pertaining to the effects of obesity on musculoskeletal integrity in both adults and children is extremely limited. Evidence has suggested that obese adults suffer from foot pathologies (Messier *et al.*, 1994). However, research pertaining to the development of foot pathologies in obese populations has been limited. Prior research in children has examined the effect of obesity on foot structure and plantar pressure distributions and stressed the need for further research as childhood obesity is increasing worldwide. By examining the effects of obesity on foot structure and sensation, foot function and plantar pressure distribution in children, a greater understanding of the potential negative consequences of musculoskeletal dysfunction in the obese child will be known. This study is therefore warranted in an attempt to limit musculoskeletal dysfunction in the obese child and the associated emotional, physical and economic costs incurred by obesity.

1.3 Research Hypotheses

Based on previous literature, it was hypothesised that, compared to non-obese children, obese children will display:

1) broader and flatter feet,
2) compromised foot sensation,
3) no difference in static conditions of rearfoot alignment,
4) greater rearfoot motion during gait, and
5) higher dynamic plantar pressure distributions in the forefoot.

1.4 Limitations

The following were acknowledged as possible limitations to the present study:

1) The subjects for the study were selected by chronological age due to budgetary and ethical constraints. Therefore, variability in the dependent variables may be higher than if the subjects had been selected by skeletal maturity.
2) Despite adequate familiarisation of the children with the testing procedures before data collection, their normal gait patterns may have been altered by the need to assess their gait under laboratory conditions.

1.5 Delimitations

This study was restricted to children who displayed normal or non-congenital forms of flatfeet and who had parental consent to participate in the study. Therefore, the subjects were not a truly random sample of the population and the findings of the study may not be applicable to other populations.

Other limitations and delimitations pertaining to the study's methodology are outlined in Chapter 3.

Chapter 2

Literature Review

Before investigating the effects of obesity on foot structure and function, it was necessary to develop an understanding of the related literature. Therefore, literature pertaining to the following areas was reviewed:

1) Childhood Obesity
2) The Foot
3) Flatfeet
4) Childhood Obesity and Foot Structure
5) Childhood Obesity and Foot Function
6) Childhood Obesity and Plantar Pressure Measurement
7) Childhood Obesity and Plantar Sensation

2.0 Childhood Obesity

Children are usually classified as obese if their weight-for-height-age is greater than 120% (Eid, 1970) or if their Body Mass Index (BMI) is above the 95th percentile for their age (Baur, 1996). However, until recently there was no consistent standard definition for childhood obesity and, therefore, research pertaining to childhood obesity was difficult to interpret and compare (Flegal, 1993; Schonfeld-Warden & Warden, 1997; Guilliame, 1999; Must *et al.*, 1999). Furthermore, obesity in children is difficult to study longitudinally as children continually grow and develop, making pre- and post-intervention comparisons of height and weight difficult to evaluate (Johnston, 1985). Despite these difficulties, there is unequivocal evidence that the incidence of childhood obesity is increasing (Kuczmarski *et al.*, 1994; Troiano *et al.*, 1995; Baur, 1996; Schonfeld-Warden & Warden, 1997; West, 1999; see Table 2.1)[*].

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[*] New international criteria for classifying childhood obesity, based on Body Mass Index (BMI) for age and gender for children 2-18 years of age, have now been published (Cole *et al.*, 2000). This provides a standard definition for identifying overweight and obese children. If employed, these criteria should now allow direct comparisons between studies as obesity in children can be universally classified.

Table 2.1 Prevalence rates for obesity and overweight in Australian children (Baur, 1996).

Study	Number studied	Age (years)	Weight-for-height age (%) >110%	>120%	Location of Study
Court *et al.* (1976)	5,347	11 - 18	9 - 20	3.5	Victoria
Dugdale & Lovell (1981)	145	11 - 12	24	N/A	Brisbane
Simons *et al.* (1982)	2,596	12 - 16	25 - 35	11.7	Sydney & Inverell
Scarlett & Lillburne (1992)	1,450	5 - 11	29	15	Inner Sydney

For example, a comparison of data from two Australian studies, (Australian College of Health, Physical Education and Recreation, 1985; Health of Young Victorians Study, 1997, unpublished) revealed an increase in the median BMI* for the children sampled in 1997 relative to those studied in 1985 (Lazarus *et al.*, 2000; see Table 2.2). Furthermore, since 1986 the occurrence of childhood obesity has increased twofold whereby children today are on average 1.2 kg heavier than their counterparts 12 years ago (Gibbons, 1998). In 1992, the prevalence of obesity among Australian school children (aged 5 to 11 years) was estimated to be 15% (Baur, 1996). Within seven years this figure has escalated such that approximately 25% of children and adolescents could now be classified as overweight or obese (Baur cited in West, 1999). Furthermore, trends in data for all age groups suggest that excess weight is more common in males than in females.

Obesity rates are also seen to be rising with increases in age, although the specific reasons causing the obesity epidemic remain undetermined. A range of factors, including environmental, psychosocial, physical, genetic, metabolic and lifestyle factors, are thought to contribute to obesity. Over the last 5 to 10 decades many factors have influenced the way in which we live our lives so that the need to physically exert oneself, both at home and in the workplace, is now minimal. For example, instead of walking, or riding a horse or bicycle, current methods of transportation include more sedentary methods such as driving cars, or taking the bus or train, thereby resulting in

* The concept of Body Mass Index is explained in Section 3.2.1.

decreased energy expenditure (James, 1995). Studies in both Canada and the United States (Gortmaker *et al.*, 1990; Pate *et al.*, 1994) have indicated that, on average, adolescents indulged in over 20 hours per week of sedentary television watching. Younger children were found to watch even more television (Dietz, 1991). Recent data published by the Australian Bureau of Statistics indicated that 52% of Australian children aged 5 to 14 years watched more than 20 hours of television or videos per week (ABS, 2000). Children are also tending to have other more sedentary behaviour patterns including prolonged sitting in classroom situations, reading a book, playing computer games, and passively socialising (Dietz & Gortmaker, 1985) with only 30% of Australia children participating in organised sporting or cultural activities (ABS, 2000). Behavioural responses have also been altered with marked changes in eating behaviours since 1945. Eating away from the home has increased and there has been a major shift in the time of day when the main meal is consumed contributing to weight gain (Blundell, 1993). For these reasons, childhood obesity is becoming an increasing problem in today's society.

Table 2.2 Age and BMI comparisons§, 1985 Australian Health and Fitness Survey and 1997 Health of Young Victorians Study samples for Victorian males and females aged 7 – 12 years (adapted from Lazarus *et al.*, 2000).

	Age at last birthday (years)											
	7		**8**		**9**		**10**		**11**		**12**	
Characteristic	**1985**	**1997**	**1985**	**1997**	**1985**	**1997**	**1985**	**1997**	**1985**	**1997**	**1985**	**1997**
Female BMI (kg/m^2)	16.0	16.5*	16.1	16.9**	16.8	17.5*	17.0	18.1*	17.9	18.5*	18.8	19.3
Male BMI (kg/m^2)	16.2	16.6*	16.3	16.8*	17.1	17.2	17.3	18.1**	18.2	18.0	18.2	18.9

§ Data are reported as median values.
* Denotes significant difference at $p < 0.05$.
** Denotes significant difference at $p < 0.001$.

Further research pertaining to obese children is urgently warranted so that efficient methods in treating this disorder, and its associated health problems, can be determined. That is, like obese adults, obese children are at risk of developing both immediate and long-term complications that can affect the individual's quality of life. These complications include cardiovascular disease, diabetes, circulatory diseases, particular forms of cancer, osteoarthritis and musculoskeletal problems (Johnston, 1985; James, 1995; Schonfeld-Warden & Warden, 1997; Must & Strauss, 1999). Although there are numerous investigations pertaining to metabolic issues and childhood obesity (Schwartz, 1979; Johnston, 1985; Baur, 1996; Schonfeld-Warden & Warden, 1997), only limited recent research was located which examined musculoskeletal problems (Kelsey, 1971; Must & Strauss, 1999), particularly foot problems, in the obese child (Riddiford-Harland *et al.*, 2000; Dowling *et al.*, 2001). The effects of childhood obesity on foot structure and function are further discussed in Section 2.3.

2.1 The Foot

The foot is an important structure in the human body as it is the foundation for stance and dynamic gait. The foot is composed of 26 bones and 28 joints that are able to support the body throughout everyday tasks (Norkin & Levangie, 1992; see Figure 2.1). Structurally, the foot is comprised of bone, ligaments (see Figure 2.2) and muscles, although it is the ligaments that play a major role in the integrity and function of the foot.

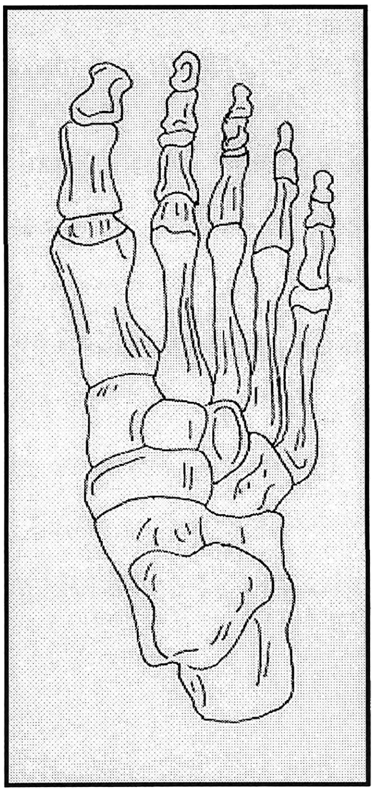
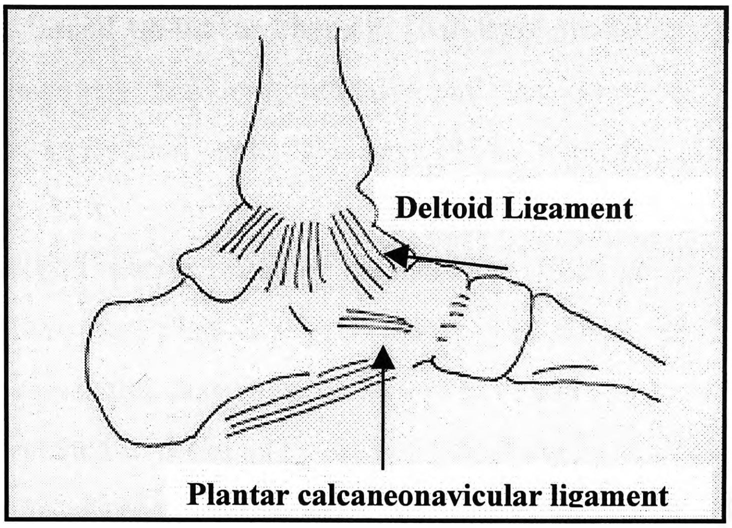
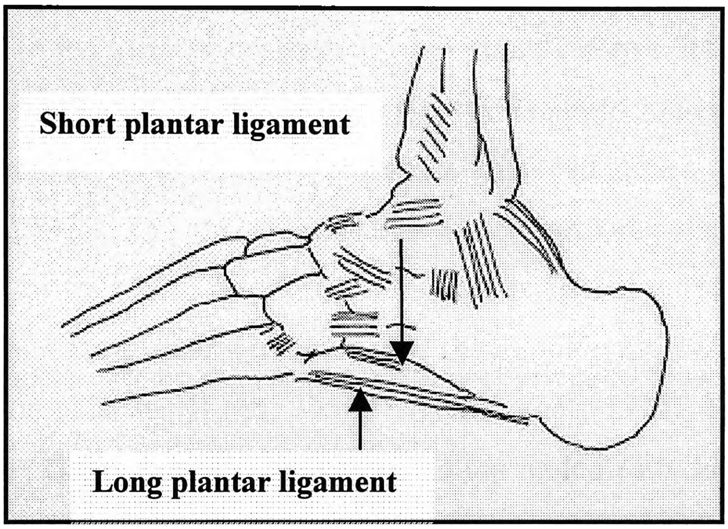


Figure 2.1 Bone structures of the foot (adapted from Hunter *et al.*, 1995, p 13).



(A)



(B)

Figure 2.2 The main ligaments of the foot; (A) medial view, and (B) lateral view (adapted from Norkin & Levangie, 1992, p 385).

The foot performs two main functions: (i) stability and (ii) mobility. Stability is achieved through a fixed arch structure, which distributes loading throughout the foot during weight bearing and can convert the foot to a rigid lever. Mobility can be achieved only by a non-rigid structure. The non-rigid structure allows the shock of weight bearing to be damped, the foot to adapt to various terrain and the damping of superimposed rotations (Norkin & Levangie, 1992). The foot also performs the essential tasks of load bearing, balance, leverage, shock absorption and protection in order to preserve oneself from injury and to move the body (Saltzman & Nawoczenski, 1995).

The ability of the foot to achieve both stability and mobility is dependent upon its unique structure. The foot has a plantar plate composed of a multi-segmental ligamentous and fascial tie-bar mechanism (windlass mechanism). This plantar plate works both transversely and longitudinally and was previously referred to as the transverse and longitudinal arch (Hicks, 1954; Stainsby, 1997). The plantar aponeurosis, long plantar, short plantar and spring ligaments are part of the plantar plate and act as powerful energy storing mechanisms (Ker *et al.*, 1987; Saltzman & Nawoczenski, 1995; see Plate 2.1 A & B). The fibres in the ligaments appear intertwined in a crosshatch arrangement, which is thought to increase the ability of the ligament to be stretched in different directions (see Plate 2.1 C).

In mechanical terms the foot is a truss with a tie-bar mechanism (see Figure 2.3). When a load is applied to the truss/tie-bar system from directly above, the two trusses, formed by the bony architecture of the foot, experience compression forces whereas the tie-bar, formed by the plantar aponeurosis, experiences tensional forces (Hicks, 1953; Hicks, 1954; Stainsby, 1997). This mechanical arrangement provides the ability for the arch-like structure of the foot to flatten during weight bearing and to reappear when the foot is unloaded. When the plantar aponeurosis is severed, the arch raising function of the foot is almost non-existent (Hicks, 1954; Kitaoka *et al.*, 1994; Arangio *et al.*, 1998). Furthermore, the plantar aponeurosis acts as a sling underneath the metatarsal heads in order to assist in dissipating plantar pressures (Sharkey *et al.*, 1999; see Plate 2.2 B). The main function of the combined longitudinal arch, particularly the medial component, is to help absorb and dissipate the reaction forces generated with each step during gait (Norkin & Levangie, 1992; Saltzman & Nawoczenski, 1995; see Plate 2.2).

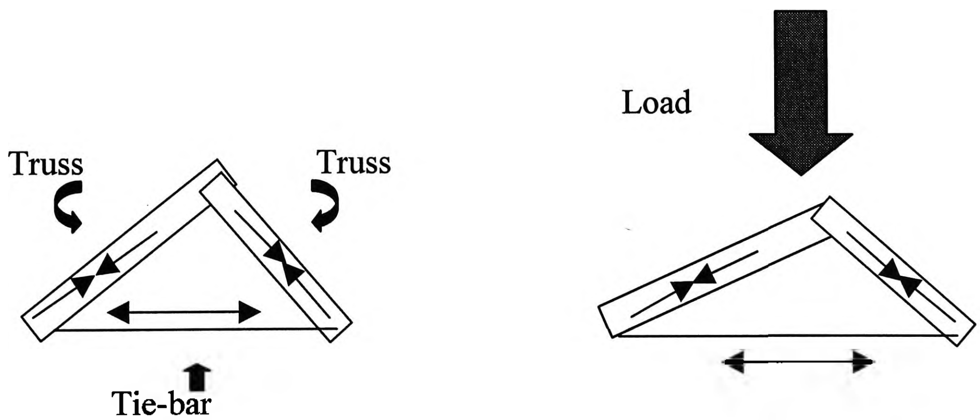


Figure 2.3. The truss and tie-bar mechanisms as described by Hicks (adapted from Stainsby, 1997, p 60).

Plate 2.1 A: The plantar plate of the foot.

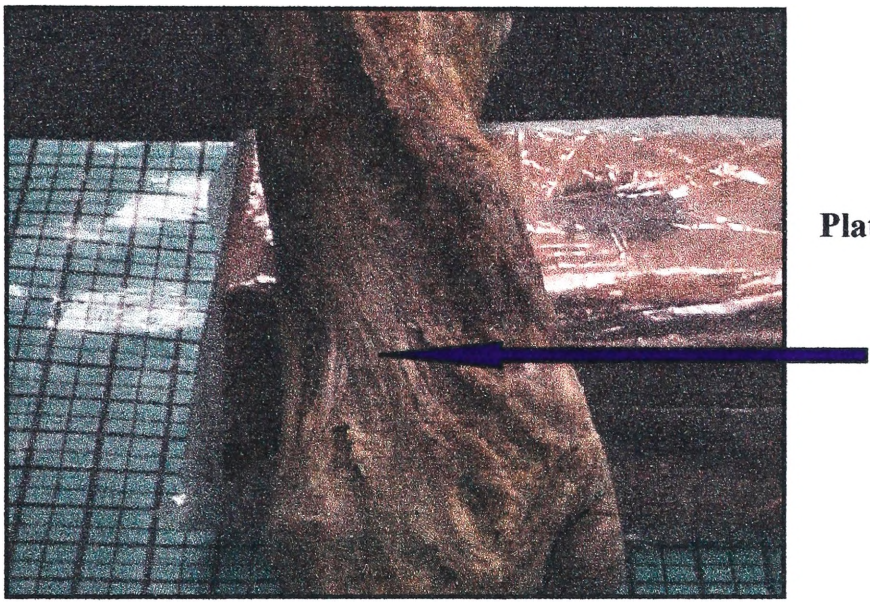


Plate 2.1 B: The plantar plate diverging for the metatarsal heads.

Plate 2.1 C: Crosshatch pattern on the plantar aponeurosis and plate.

N.B: All photographs in the plates were taken of a dissection undertaken during the thesis to enhance my knowledge of the foot and its associated anatomical structures.

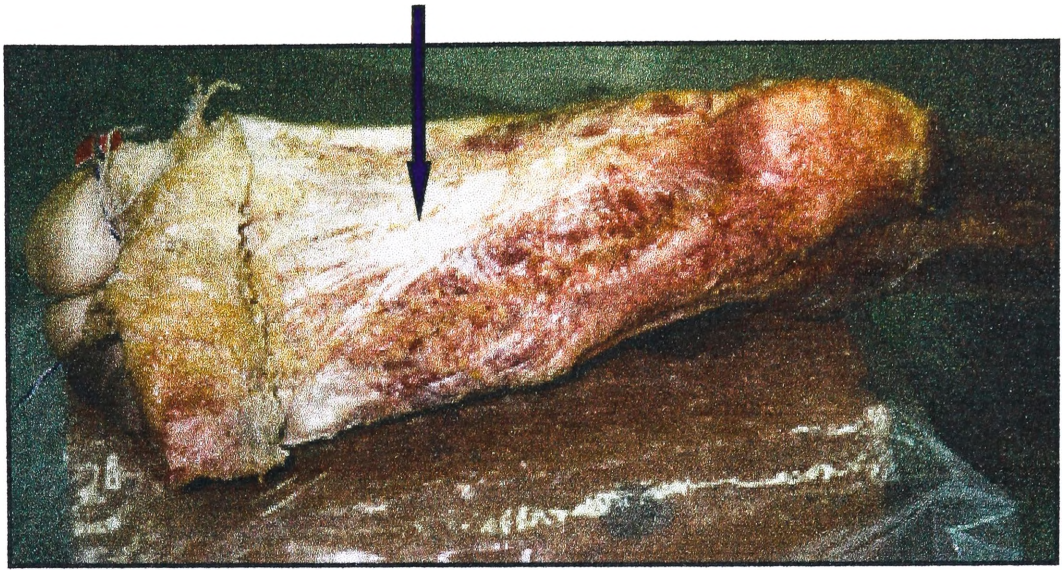


Plate 2.2 A: The plantar plate diverging to insert under the metatarsal heads.

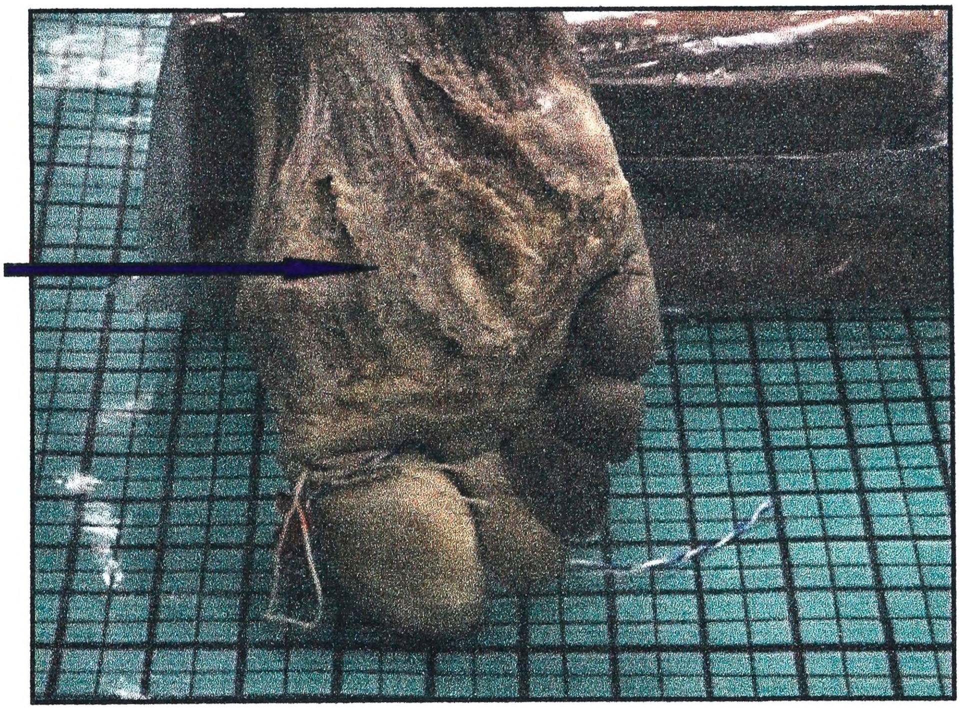


Plate 2.2 B: The plantar plate inserting on to the metatarsal heads.

The foot is able to support and absorb very high loads (Kapandji, 1987; Newman, 1980; Mueller & Diamond, 1988; Robbins & Guow, 1991; Hockenbury, 1999). During walking, the peak vertical forces acting on the foot can reach 120% of body weight (Novel$_{gmbh}$, 1998). When walking 1.6 km, an individual weighing 67 kg has been estimated to absorb 64.5 tonnes on each foot (Mann, 1982; Cavanagh *et al.*, 1987). As a consequence of having to consistently withstand such high loading, foot pathologies frequently occur. For example, increased stress or pressure on the metatarsal heads may cause pain and discomfort. A tight Achilles tendon has also been known to increase forefoot loading in the stance phase of gait, in turn, placing stress on the metatarsal heads (Grant *et al.*, 1997; Armstrong *et al.*, 1999; Hockenbury, 1999). High pressures on the forefoot have been linked to arch collapse and have been documented in diabetic patients (Barry *et al.*, 1993).

The foot absorbs shock in two main ways. Firstly, the specialised fat pads located on the plantar aspect of the foot beneath the metatarsal heads and heel regions of the foot, directly absorb and dissipate the forces exerted on the feet when standing and during dynamic tasks (Cavanagh, 1999; see Plate 2.3). These two pads consist of fat filled microchambers encapsulated in fibroelastic tissue (Kimani *et al.*, 1984; Gooding *et al.*, 1985). Throughout these chambers are vibration sensitive Pacinian corpuscles (Jahss *et al.*, 1992). The function and mobility of the plantar fat pads have not been well documented, although the importance of the metatarsal head fat pad to reduce pressure has been shown in neuropathic feet with ulceration caused by a shift in the metatarsal head fat pad (Myerson & Shereff, 1989; Cavanagh *et al.*, 1997). In some adults a fat pad also exists in the lateral midfoot region, although, the present reasoning behind this occurrence is unknown (see Plate 2.3 B & C). Although these fat pads help to prevent injury, no material, at the present time, has been found which can replicate the shock absorption capability of the plantar fat pads (Saltzman & Nawoczenski, 1995; Jorgensen *et al.*, 1989; Garcia *et al.*, 1994).

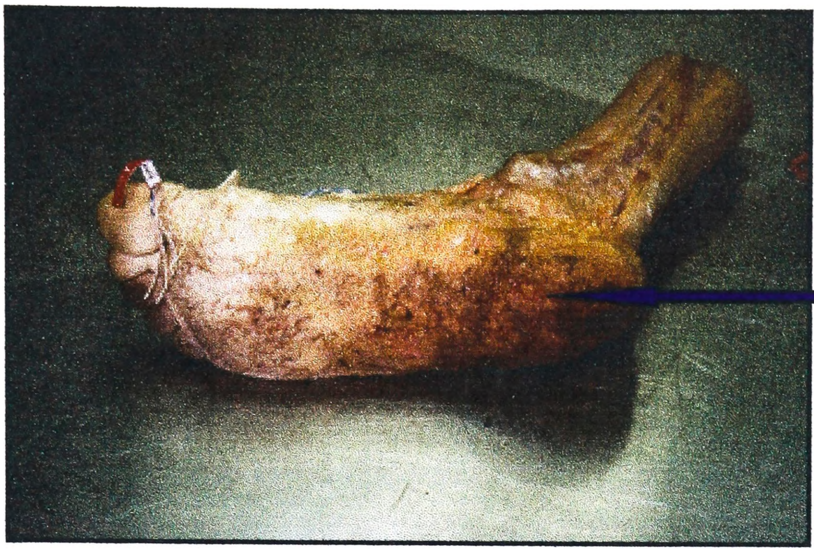


Plate 2.3 A: The plantar fat pad.

Plate 2.3 B: A plantar fat pad in the midfoot region - posterior view.

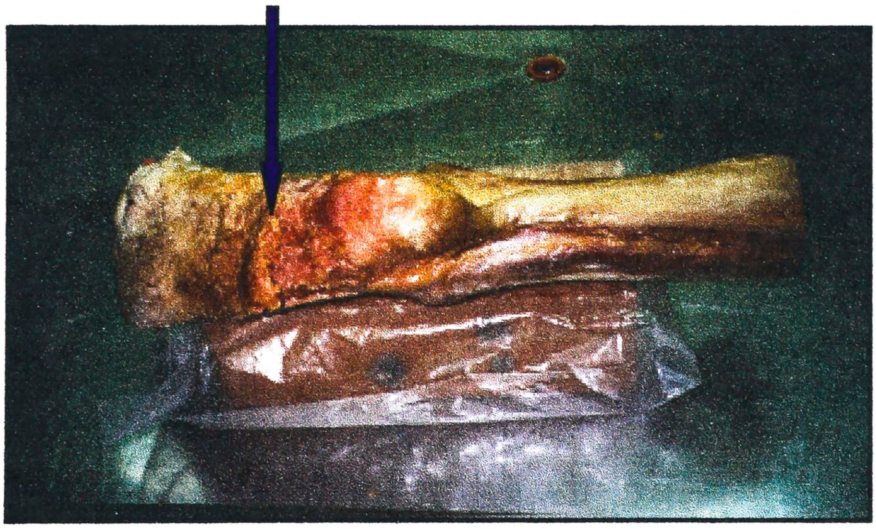


Plate 2.3 C The plantar fat pad after removal of the heel fat pad – plantar view.

The second method by which the foot absorbs shock is via mobility of the foot that allows the ligaments and muscles to help absorb the forces generated with each step (Ker *et al.*, 1987). Ligaments do not usually incur physiological fatigue and therefore offer a greater resistance to stress compared to muscles (Platzer, 1992). The muscles of the foot provide a secondary support role for the longitudinal arch by maintaining the arch during dynamic tasks. The role of extrinsic and intrinsic muscles in maintaining stability of the arch has not been clarified for dynamic conditions although many researchers have found that these muscles play no major role in stabilising the foot in static tasks (Basmajian & Stecko, 1963; Mann & Inman, 1964). Although providing stability to the foot, if ligaments are stretched beyond their elastic limit they are unable to reform to their original state, thus changing the ability of the ligaments to absorb forces. Huang *et al.* (1993) found that when the arch of the foot was loaded, the height of the arch decreased. Repeated loading may weaken tissues in the foot causing a degree of collapse to occur (see Figure 2.4). Therefore, excessive stretching of the ligaments of the longitudinal arch may result in foot pathologies such as flatfeet.

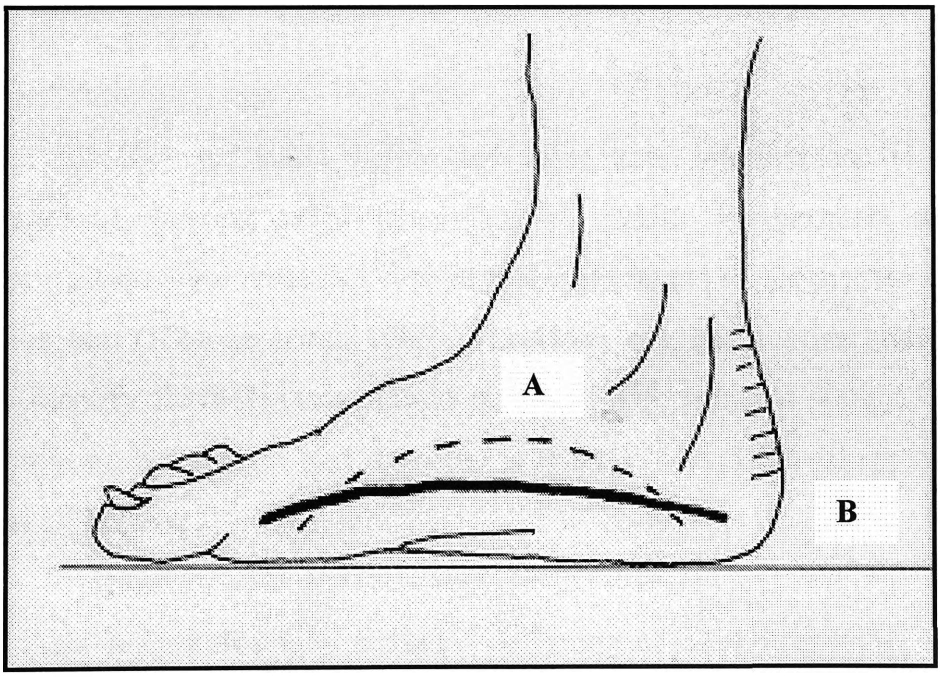


Figure 2.4 (A) A normal longitudinal arch, and (B) a depressed longitudinal arch (Kapandji, 1987, p 239).

2.2 Flatfeet

Flatfootedness, medically termed *pes planus*, is caused by loss of the medial portion of the longitudinal plantar plate (Chadha *et al.*, 1997) and is a common complaint in industrialised societies. For example, 4,621,000 Americans complained of the lay-term "fallen arches" or flatfeet according to the National Center for Health Statistics (Peterson, 1994). This abnormality has the tendency to make the foot supple (or prone to collapse) because the foot lacks the ability to supinate in order to form a rigid lever during push-off in gait (Bordelon, 1983; Bordelon, 1985). There are many types of flatfeet, including relaxed flatfoot, congenital flatfoot, and rigid flatfoot, which are caused by a variety of mechanisms. Relaxed flatfoot is indicated by the presence of a lowered longitudinal arch height during static weight bearing but a normal arch structure during dynamic tasks such as standing on toes (Omey *et al.*, 1999). As this foot structure is only pathological statically, it is thought that ligament laxity is the mechanism for relaxed flatfoot. Congenital flatfoot is a rare condition whereby the foot is in a position of calcaneovalgus, folding laterally on itself (Cailliet, 1980). Rigid flatfoot is where a reversal of the concavity of the normal longitudinal arch is displayed (Platzer, 1992) and is evident during both static weight bearing and dynamic gait. These latter two conditions are difficult to treat as they involve structural deformity to the longitudinal arch whereas relaxed flatfoot is only functional and can therefore be modified (Cailliet, 1980).

Alignment of the foot and ankle differs depending upon whether one is non-weight bearing or statically bearing weight (Shereff *et al.*, 1990). Furthermore, radiographic evidence has indicated that there is a change in the alignment of the plantar plate during loading of the foot (Kitaoka *et al.*, 1995). Therefore, any quantitative analysis of foot structure to identify flatfootedness should be made with subjects weight bearing and should incorporate both static and dynamic assessments to differentiate between the various types of flatfeet.

At present, there is no universally accepted definition of what constitutes normal arch height, complicating the definition of pathological foot problems. However, arch height in adults has been related to the occurrence of tibial, femoral and metatarsal stress fractures (Giladi *et al.*, 1985; Simkin *et al.*, 1989). There is also the tendency for individuals with flatfeet to have a tight Achilles tendon, which will, in turn, alter forefoot plantar distributions and limit dorsiflexion (Harris & Beath, 1948; Beauchamp, 1987). Clinical evidence of a planus foot type has various foot pathologies associated with it including plantar fasciitis, heel spur syndrome and hallux abducto valgus (Mahan, 1992; Schoenhaus & Cohen, 1992). Therefore, flatfeet can have pathological consequences and, in turn, affect quality of life.

As children grow their foot structure also develops. Gould *et al.* (1989) examined the development of the longitudinal portion of the plantar plate in the feet of children over the first four years of life. In the first year of life all children displayed flatfeet. However, in the second year of life, initial development of the longitudinal portion of the plantar plate was evident, regardless of the particular footwear worn by the children. This development continues until the age of 6 years, after which time development of the plantar plate is complete and the child's foot structure displays characteristics of the adult foot (Beauchamp, 1987; Hennig *et al.*, 1994). However, Staheli (1987) reported that flatfeet were commonly displayed in both infants and children and could even be seen normally in adult feet without pathological consequences.

Many lower extremity injuries incurred by children, particularly between 6 years and the late teens, relate to foot problems (Subotnick, 1979). Long-term excessive abnormal function, such as excessive pronation, may lead to irreversible soft tissue and bone deformation of the lower extremity (Subotnick, 1975; 1979). Often children with foot problems are treated using the same regimes used for adult foot pathologies. However, due to immature structures and the functional components in the young developing child's feet, this treatment can be detrimental. Normative data pertaining to foot pathologies in children is needed to encompass various growth levels in children in order to ensure correct diagnosis and treatment (Schuster & Skilar, 1991).

Although the long-term effects of flatfeet in children have not been fully established, flatfootedness in adults has been linked to excessive pronation in both static stance and dynamic gait (McKenzie, 1987). Flatfeet have also been found to predispose army personnel to stress fractures and other foot traumas (Kaufman cited in Cole, 2000). A lower limb pathology may be exacerbated in obese or overweight individuals due to increased mechanical loading of the lower limbs caused by their additional mass. Furthermore, if an individual wears ill-fitting shoes, such as high heels, there is a tendency for the ligaments in the longitudinal arch of the foot to modify their position, altering their force absorption capacity, which may, in turn, intensify any foot dysfunction. Previous research has shown that subjects with flatfeet displayed an increased loading under the midfoot region and an increased peak loading measured on the lateral aspect of the forefoot (Stott *et al.*, 1973). Heavier adult subjects have also been found to increase peak pressure in the midfoot and lateral forefoot regions during midstance of gait (Hennig *et al.*, 1994). The pathological flatfoot typically has a valgus calcaneus imposing a pronatory gait pattern on the lower limb (Smith *et al.*, 1992; Mann, 1993). This pattern results in a medial shift in body weight, with an accompanying poor propulsive lever compared to normal gait, and may increase the potential risk of developing foot pathologies (Bauer *et al.*, 1996).

2.3 Childhood Obesity and Foot Structure

As a child's weight increases, greater stress is placed on the ligamentous and muscular structures of the foot (Donatelli, 1990). Excessive increases in these weight bearing forces may cause microtrauma to the ligaments and muscular structures, damaging soft tissue and increasing the risk of joint collapse and flatfeet, particularly in obese individuals (Nigg, 1986; Donatelli, 1990; Norkin & Levangie, 1992).

It has been suggested by various authors that obesity may have a negative effect on the lower extremity (Gehlsen & Seger, 1980; Vitasalo & Kvist, 1983; Messier & Pittala, 1988; Messier *et al.*, 1994). However, only two investigations were located which directly examined the association between foot structure and obesity in children (Riddiford-Harland *et al.*, 2000; Dowling *et al.*, 2001). Results from both studies indicated a general trend for obese prepubescent children to have flatter feet when compared to their non-obese peers. This was evident by obese children displaying an increased Chippaux-Smirak Index (CSI) and a decreased Footprint Angle (FA) relative to non-obese children (Table 2.3; see Section 1.0). However the consequences of this greater foot contact area in obese children is unclear.

Table 2.3 Footprint Angle (FA) and Chippaux-Smirak Index (CSI) data* reported by Riddiford-Harland *et al.* (2000) and Dowling *et al.* (2001).

Variable	Non-obese[1]		Obese[1]		Non-obese[2]	Obese[2]
	Left	Right	Left	Right	Pooled left & right feet	
FA (°)	46.9 ± 11.4	46.1 ± 10.9	38.1 ± 14.7	37.6 ± 14.0	45.0 ± 5.1	33.1 ± 13.9*
CSI (%)	20.6 ± 12.9	23.4 ± 12.4	36.3 ± 14.4	36.8 ± 14.0	23.8 ± 13.0	46.3 ± 13.3*

1 Data from Riddiford-Harland *et al.* (2000).
2 Data from Dowling *et al.* (2001).
* Data are presented as means ± standard deviation.

Children who have excessive valgus pronated feet tend not to be very physically active (Beauchamp, 1987). Therefore, obesity and associated foot problems may contribute to the relatively sedentary behaviour of obese children (Beauchamp, 1987). During prepubescent development, it is unknown if a plantar fat pad remains or develops in the instep of the obese child's foot, thereby causing what appears to be a flatfoot. If a plantar fat pad remains in the medial midfoot region it is undetermined what influence it would have on the longitudinal arch. It is also unknown if there is some other structural dysfunction present in the feet of obese children which may cause the longitudinal arch to collapse, resulting in an increased foot contact area such as that noted by Riddiford-Harland *et al.* (2000) and Dowling *et al.* (2001). A recent study involving diabetic patients found that the plantar aponeurosis, which is part of the plantar plate, became detached and increased the potential risk of foot problems for this special population (Stainsby, personal communication, 1999). This may have negative implications for obese individuals and may explain the flattening of the arch-like structure in their foot. However, although the studies by Riddiford-Harland *et al.* (2000) and Dowling *et al.* (2001) have examined the effects of obesity on external foot parameters of flatfootedness, no studies have examined the consequences of obesity on other parameters that characterise foot structure. In order to fully understand the effects of obesity on foot structure, there is a need to examine variables other than just those derived from footprints.

2.4 Childhood Obesity and Foot Function

Although it has been implied that flatfootedness can alter foot function during gait, no studies were located which have examined the effects of obesity on the kinematics of dynamic foot function in children. However, three studies were identified that have examined the effects of childhood obesity on gait in general. These studies have revealed that obese children displayed lower cadence, lower velocity, a longer stance period and a longer duration of the gait cycle compared to their non-obese counterparts (Hills & Parker, 1991; Hills & Parker, 1992). In contrast, David *et al.* (1999) found no difference in the temporal parameters of gait between obese and non-obese children. Only one study was located that investigated the effects of obesity on foot function in adults (Messier *et al.*, 1994). In this study obese females displayed significantly greater rearfoot motion, foot angles and Q angles compared to their normal weight counterparts. A further interesting finding, relevant to the present study, was the significantly greater forefoot abduction displayed by the obese adult females during walking relative to the non-obese controls. This study highlighted potential detrimental effects of severe obesity on the mechanics of gait through a trend for abnormal rearfoot varus at heel strike moving through to evert the foot during mid stance. However, the effect of obesity on the rearfoot motion of children during walking has not been investigated.

Rearfoot angle has been clinically used to determine heel valgus during stance (Vitasalo & Kvist, 1983; Smith & Wagreich, 1984; Sobel *et al.*, 1999). Greater than 5° of heel valgus has been suggested to alter plantar pressures and may affect other gait parameters during stance (Lelievre, 1970). In healthy adults the normal range for rearfoot angle values are between 3.5 to 7° of valgus (McPoil & Cornwall, 1994; Astrom & Arvidson, 1995; McPoil & Cornwall, 1996). These adult rearfoot angle values have also been found to be displayed by children as young as 5 (McCrea, 1985) and 7 years of age (Root *et al.*, 1971; Valmassy, 1996), and up to 16 years of age (Sobel *et al.*, 1999). However, the only study to examine the effect of obesity on static rearfoot alignment in children was that conducted by Riddiford (2000), whereby subjects stood in a comfortable stance on a raised box. Results of this investigation found no effect of obesity on static calcaneal and tibial angle in prepubescent children. However, lower limb alignment was only assessed statically and only with the children adopting one stance; feet apart. It is postulated that if children are required to stand with their heels together lower limb alignment in obese children would be compromised as obese children tend to have more adipose tissue on their thighs and this may alter the Achilles tendon insertion angle, in turn, influencing rearfoot angle values.

Alignment of the bony architecture of each child's rearfoot would ideally be examined internally using technology such as x-rays. However, this may not be a safe or ethical method to use with populations such as children due to radiation levels. Alternatively, new methods are now available to examine the external anthropometry of the foot (Parham *et al.*, 1992) and could be used to better understand the effects of obesity on foot structure in obese children.

Assessment of foot function would not be complete without examining the range of motion of the foot/ankle complex. Dorsiflexion and plantar flexion range of motion is important to examine as limited joint mobility may alter foot function in both stance and gait and has been shown to alter plantar pressure distributions (Boone & Azen, 1979; Mueller *et al.*, 1989).

2.5 Childhood Obesity and Plantar Pressure Measurement

Although obesity in children has been related to flatfootedness (Riddiford-Harland *et al.*, 2000; Dowling *et al.*, 2001) and has been associated with increased forefoot loading (Dowling *et al.*, 2001), research pertaining to the effects of obesity on loading of the feet is extremely scarce. Recent technological advances have enabled the development of sophisticated measurement devices to assess loading of the feet during activities of daily living by quantifying pressure exerted on the plantar surface of the feet (Barton & Lees, 1995). Pressure is derived by measuring the perpendicular force applied per unit area of the sensor it is in contact with (Nigg & Herzog, 1995; see Equation 2.1).

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \qquad \textbf{Equation 2.1}$$

Traditionally, pressure measurement was undertaken using a variety of methods such as rubber pyramids in contact with a glass plate and a film camera (Elftman, 1934; Miura *et al.*, 1974), through to light interference methods (Arcan & Brull, 1976) and relatively simplistic devices such as the use of ink mats or depressible foam (Kalpen, 1998). However, radical changes in the development of commercially available pressure measurement equipment were made between 1980 and 2000 with the development of electronic pressure measurement devices (Chodera & Lord, 1960; Hennig & Nicol, 1978; Cavanagh & Hennig, 1982; Duckworth *et al.*, 1982; Aritomi *et al.*, 1983; Nigg & Herzog, 1995).

At present there are a variety of electronic pressure sensors available but their ability to provide accurate and reliable pressure values varies due to design limitations of each sensor system. The main sensors utilised to measure plantar pressures are conductive and capacitive sensors. The conductive sensor is based on measuring the change in electrical resistance of a circuit in response to a load placed on it (Nigg & Herzog, 1995). The main benefits of using a conductive sensor are the low expense involved, the thin sensors available, the high local resolution and the shape of the sensor. However, conductive sensors have large hystereses, high sensitivity to shear forces, instability during long term loading of the sensor, temperature sensitivity and the restoring forces are not clearly defined (Kalpen, 1998). Therefore, capacitive sensors were developed to overcome these limitations of conductive sensors.

Capacitive sensors are designed with an elastomer located between two plates. One plate is connected to a transmitter and the other plate is connected to a receiver. As a force is applied to the first plate, the elastomer compresses, changing the distance between the two plates, which causes an electric current to be generated (see Figure 2.5). Advantages of using capacitive sensors are that they have a well-defined restoring force, a small hysteresis, small temperature sensitivity, conform well to three dimensional objects, are thin and the direction of force application can be determined. As a well-defined restoring force is one of the most vital properties of a sensor suitable for measuring plantar pressures (Kalpen, 1998), capacitive sensors have been selected as the preferred sensor type for this thesis. The use of capacitive sensors to assess plantar pressure distributions is further discussed in Section 3.1.8. Plantar pressure analysis is a good quantitative indicator of foot function during dynamic gait and can indicate whether there are potential negative consequences associated with obesity-related flatfootedness.

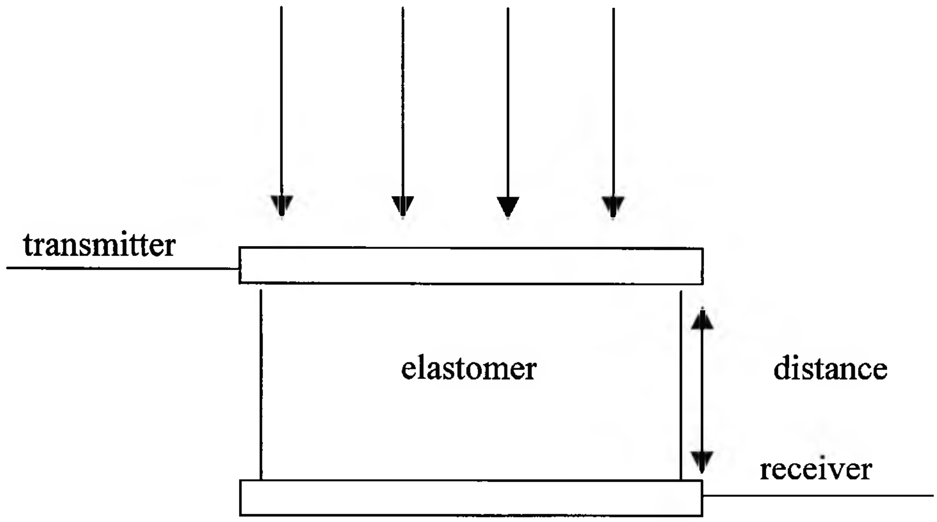


Figure 2.5 A capacitive sensor (adapted from Kalpen, 1998).

Children tend to have larger foot dimensions per kilogram of body mass than adults. Theoretically, this should reduce the relative pressure children experience under their feet compared to adults (Hennig *et al.*, 1994). Betts *et al.* (1980) reported that in normal children, peak pressure ratios were 1.94 times greater in the heel region compared to the forefoot in stance.

Very little research has examined the effects of obesity on plantar pressure distributions in either children or adults. In adults a relationship between midfoot pressure distribution and relative body weight has been reported (Hennig *et al.*, 1994). That is, as body weight increased, loads on the longitudinal portion of the plantar plate increased (Smahel, 1980). However, this relationship between body mass and pressure in adults was not found by Cavanagh *et al.* (1987). Studies have indicated that plantar pressures increase with age although this increase in pressure is thought to be negligible as body weight also increases with age (Duckworth *et al.*, 1982). Hennig *et al.* (1998) noted that in adults there was an effect of overweight on plantar pressures compared to normal weight adults in both 50% body weight stance and during walking. The location of these peak plantar pressures in overweight adults differed in males and females.

Only two studies were found which examined the effects of obesity in children on plantar pressure distributions (David *et al.*, 1999; Dowling *et al.*, 2001). Dowling *et al.* (2001) reported that both statically and dynamically, total foot peak force and peak area were significantly greater in the 13 obese children tested compared to their 13 non-obese counterparts (see Table 2.4). As this increase in the force generated by the obese children was distributed over a larger total foot area, only negligible differences were noted in the peak plantar pressures experienced by the two subject groups across their feet. However, when the foot was divided into rearfoot and forefoot sections, the obese children experienced significantly greater peak pressures in the forefoot compared to the non-obese children (see Table 2.4). David *et al.* (1999) also reported higher forefoot pressures and area for obese children although these values were not significantly higher than their leaner counterparts.

This significantly increased pressure in the forefoot region noted by Dowling *et al.* (2001) is of major concern, as the forefoot region is comprised of small bones which have a decreased ability to dissipate the forces associated with dynamic walking tasks. It was therefore postulated that obese children may have an increased potential risk of developing foot pathologies, including stress fractures, as a consequence of higher forefoot pressures during walking (Dowling *et al.*, 2001). It was also hypothesised that foot discomfort associated with these increased forefoot plantar pressures may discourage obese children from participating in physical activity, thereby perpetuating the cycle of obesity. As these findings may cause detrimental health implications for the obese child, further research pertaining to the effects of obesity in children on plantar pressure distributions is urgently warranted. We need to ascertain if the findings of Dowling *et al.* (2001) and the trends noted by David *et al.* (1999) are typical for other samples of obese children and, if so, exactly where on the forefoot these areas of high pressure are located. That is, the analysis undertaken for the pressure parameters by Dowling *et al.* (2001) was basic, and therefore a more comprehensive analysis of the pressure distributions generated by obese children may provide more specific information about the locations of the peak pressures and when they occur in the roll over process. It is also unknown whether the increased plantar pressures generated during gait by obese children affect other aspects of foot function such as sensation on the plantar surface of the foot.

Table 2.4 Dynamic peak, rearfoot and forefoot force, area and pressure for the obese (n = 13) and non-obese (n = 13) subjects under both loading conditions and *p*-values derived for each source of variance for peak force, area, pressure, rearfoot force, area, pressure and forefoot force, area and pressure data with loading condition and the obesity factor (Dowling *et al.*, 2001).

Variable	Obese Unloaded Mean	Obese Loaded Mean	Non-obese Unloaded Mean	Non-obese Loaded Mean	Loading effect *p*-value	Obesity effect *p*-value	Loading x Obesity *p*-value
PF# (N)	478.1 ± 102.0	558.9 ± 119.3	318.4 ± 56.8	365.6 ± 61.8	<0.001*	<0.001*	0.339
PA (cm^2)	97.1 ± 11.9	101.1 ± 12.0	74.3 ± 9.2	78.1 ± 9.9	0.065	<0.001*	0.973
PP ($N \cdot cm^{-2}$)	38.0 ± 12.6	43.4 ±17.3	33.9 ± 8.8	38.8 ± 11.1	0.044*	0.087	0.910
RF (N)	341.0 ± 93.6	399.2 ± 91.9	227.5 ± 33.9	260.3 ± 38.4	0.001*	<0.001*	0.360
RA (cm^2)	37.0 ± 6.7	39.3 ± 6.4	23.6 ± 4.9	25.1 ± 5.0	0.087	<0.001*	0.719
RP ($N \cdot cm^{-2}$)	27.9 ± 6.3	31.9 ± 7.0	30.3 ± 8.3	34.1 ± 10.7	0.019*	0.155	0.946
FF (N)	446.6 ± 83.9	515.3 ± 89.5	311.0 ± 55.0	354.4 ± 60.8	<0.001*	<0.001*	0.384
FA (cm^2)	48.7 ± 5.6	50.0 ± 5.7	39.0 ± 4.1	41.3 ± 4.1	0.065	<0.001*	0.617
FP ($N \cdot cm^{-2}$)	36.4 ± 13.0	42.3 ± 17.8	30.0 ± 7.8	34.7 ± 10.0	0.036*	0.006*	0.813

* Denotes significant difference

\# PF = Peak force, PA = Peak area, PP = Peak pressure, RF = Rearfoot force, RA = Rearfoot area, RP = Rearfoot pressure, FF = Forefoot force, FA = Forefoot area, FP = Forefoot pressure.

2.6 Childhood Obesity and Plantar Sensation

2.6.1 The Somatosensory System

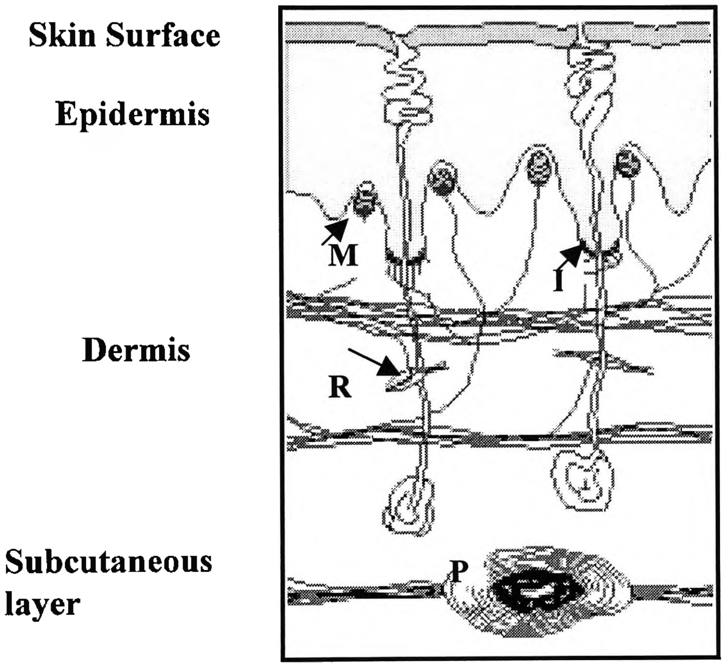
The somatosensory system allows the body to react to its forever changing environment in order to protect the body from harm through exteroceptors located near the surface of the body (Tortora & Anagnostakos, 1990). The somatosensory system plays an important role in the foot as it provides information in order for the foot to accommodate to various terrains. To achieve this, the system has the ability to mediate different sensations, including touch, pressure, thermal, vibration, or proprioception (Tortora & Anagnostakos, 1990).

There are three main types of cutaneous sensations, including tactile sensations (touch, pressure and vibration), thermoreceptive sensations (cold and heat) and pain (Tortora & Anagnostakos, 1990; Waxman & de Groot, 1995). The receptors to detect these sensations are unequally distributed in a *punctate distribution* around the body, allowing certain body parts to be more sensitive to specific sensations compared to another body part. The foot must provide the body with important information about the environment in which it moves, particularly via contact between the plantar surface of the foot and the supporting surface. Therefore, there are numerous receptors on its plantar surface to detect the cutaneous sensations (Waxman & de Groot, 1995). There are at least four different types of tactile receptors which are found in the feet, including Meissner's corpuscles, Pacinian corpuscles, Merkel's disks and Ruffini end-organs in addition to free nerve endings (see Figure 2.6).

Free nerve endings are classified as nociceptors, found everywhere in the skin and other tissues. These nociceptors function to detect pain and will respond to any stimuli if it is strong enough to cause damage to any tissues (Tortora & Anagnostakos, 1990). The nociceptors play an important role in the foot as they provide quick information to the rest of the body if the foot steps on something sharp or likely to cause pain.

Mechanoreceptors in the foot detect mechanical deformation of the receptor or surrounding tissue and convert this stimulus into a nervous impulse (Tortora & Anagnostakos, 1990). This nervous impulse can provide the body with information about the depth of indentation, rate at which the stimulus is occurring and shape of the stimulus (West, 1990). Tactile senses in the foot include touch, pressure, and vibration and are interrelated (Guyton & Hall, 1996). Touch sensation refers to stimulation of tactile receptors in the subcutaneous tissues, pressure sensation results from deformation of deeper tissues whereas vibration results from rapidly repeated sensory signals (Guyton & Hall, 1996). The mechanoreceptors on the plantar aspect of the foot are embedded in the glabrous skin covering its surface. The special feature of this skin type is an absence of hair. Dermal ridges also add to mechanoreception of glabrous skin. Four types of sensory units, two rapidly adapting and two slow adapting sensory units, innervate glabrous skin.

Rapidly adapting sensory units include Meissner's corpuscles and Pacinian corpuscles. The egg-shaped Meissner's corpuscles encompass elongated encapsulated nerve endings that excite large type A-Beta (A-β) myelinated sensory nerve fibres (Tortora & Anagnostakos, 1990). Meissner's corpuscles can adapt very rapidly when stimulated. They are also very sensitive to light movement across the skin and low frequency vibrations in the range of 30 to 40 Hz. Meissner's corpuscle density declines with age. At 3, 32, and 83 years of age, the density of these corpuscles is approximately 69, 27, and 8 per mm^2, respectively (Cauna, 1965; Quilliam, 1977). Other glabrous skin mechanoreceptors decline with age as well (Cauna, 1965; Quilliam, 1977).



M = Meissner's corpuscles, I = Merkel's disks, R = Ruffini end-organs and P = Pacinian corpuscles.

Figure 2.6 Sensory input cells in the skin.

The second type of rapidly adapting sensory units in the feet are Pacinian corpuscles. These corpuscles are elongated oval-shaped multi-layered capsular end-organs (West, 1990) and are stimulated by pressure, rapid movements of tissues and can adapt in a few hundredths of a second. Pacinian corpuscles can detect vibrations from 30 to 800 Hz as they respond rapidly to change (Crouch, 1985; Guyton & Hall, 1996). However, these corpuscles respond optimally at 250 to 300 Hz (West, 1999). They are also important in detecting vibration or changes in the mechanical state of the tissue. As this mechanoreceptor can adapt quickly to change, it can redistribute the pressure acting on it in order to maintain an equal pressure distribution throughout the mechanoreceptor, thus applying even stimuli to the central nerve fibre (Crouch, 1985; Guyton & Hall, 1996).

Slowly adapting sensory units include Merkel's disks and Ruffini end-organs. Merkel disks are often grouped together in a receptor organ called an Iggo dome receptor, projecting upwards on the underside of the epithelium of the foot. As the Merkel's disks protrude outward, they form extremely sensitive receptors, which are innervated by type A-β single myelinated nerves. Merkel's disks are slow adapting, although very persistent (Sage, 1984; Guyton & Hall, 1996). The plantar surface of the foot has large numbers of Merkel's disks distributed through the skin and subcutaneous layers (Ziegler *et al.*, 1988).

Ruffini end-organs are oval shaped and have a tough connective tissue sheath inside their nerve fibre branches and end in small free knobs. They are embedded in the subcutaneous tissue and are considered to detect heavy and continuous touch sensations and pressure (Crouch, 1985).

Most information about the mechanoreceptors within the foot has been based on animal studies, especially the footpads of cats (Iggo *et al.*, 1977; Hamalainen *et al.*, 1984). Relatively few studies have examined human mechanoreceptors in the foot (Vedel & Roll, 1982; Ribot-Ciscar *et al.*, 1989; Kekoni *et al.*, 1995; Nurse & Nigg, 1999). However, numerous tests have been developed to test sensory function in the human foot. For example, pressure sensation can be tested using instruments including Semmes-Weinstein monofilaments, fingertips, aesthesiometer and cotton tips. Vibration sensation can be tested using a tuning fork or a vibrometer. Methods for assessing plantar sensation are further discussed in Section 3.1.5.

Despite an abundance of sensory tests, there is limited information available pertaining to foot sensation in adults and even less information regarding the feet of children and adolescents. Therefore, there is the need to investigate protective sensory components of children's feet and how they may be affected by long-term weight bearing associated with obesity.

2.6.2 Foot Sensation and Gait

The ability to sense touch, pressure, and vibration via receptors on the plantar surface of the foot is vital to provide information pertaining to one's external surroundings. For example, with every step we take during gait the foot experiences a variety of sensations that indicate what the foot itself is doing and how the external surrounding is reacting to it. Interference of the sensory input to the foot may cause a disturbance in posture, muscle activation patterns, influence the kinetics and kinematics of gait and may produce a redistribution of plantar pressures (Chen *et al.*, 1995). Thus, as the feet are the body's main base of support, compromised foot sensation can increase the potential for accidents to occur.

One population at risk for developing sensory nerve deficits, which potentially affect foot sensation, are diabetic patients, many of who develop diabetic neuropathies. As obese individuals are at a high risk of developing Type II diabetes, and the associated neuropathies, they should also be aware of possible risks to their feet. However, although studies have allowed insight into plantar pressure distributions and sensory input relationships with the human foot (Chen *et al.*, 1995; Nurse & Nigg; 1999), they have not investigated the effects of obesity on foot sensation.

2.7 Summary

The literature currently available pertaining to childhood obesity is mainly focussed upon metabolic and genetic dysfunction. There is a paucity of research available regarding musculoskeletal problems in the obese child, especially research investigating foot pathologies. Podiatric and biomechanical research is available which has investigated foot pathologies, including flatfeet, although not particularly in reference to the effects of loading on these pathologies. Furthermore, only limited research is available regarding sensory foot function in adults let alone children who are obese. The consequences of compromised foot structure and function, including decreased foot sensation, can be severe, potentially affecting an obese individual's physical activity level that may, in turn, perpetuate their degree of obesity. Therefore, the aim of this study was to investigate the effects of obesity in children, especially with regard to foot structure and function, foot sensation and plantar pressure distributions.

Chapter 3
Methods

3.0 Subjects

Four female and six male obese children (6 - 12 years of age) without other pathologies unassociated with their obesity were selected as experimental subjects for the present study. These subjects were recruited from three venues: (1) Kidfit, an obesity exercise clinic, Wollongong, New South Wales; (2) Kids Uni, an after school child care centre, Wollongong, New South Wales; and (3) Kinross Wolaroi Preparatory School, Orange, New South Wales. The number of obese subjects represented all consenting 6 to 12 year old children at the three venues who were classified as obese according to recently published international BMI criteria for children aged 2 to 18 years (Cole *et al.*, 2000).

Table 3.1 Classification of the subjects into overweight and obese categories based on their BMI (adapted from Cole *et al.*, 2000).

	Overweight (kg/m^2) BMI		Obese (kg/m^2) BMI	
Age	**Male**	**Female**	**Male**	**Female**
6	17.6	17.3	19.8	19.7
7	17.9	17.8	20.6	20.5
8	18.4	18.3	21.6	21.6
9	19.1	19.1	22.8	22.8
10	19.8	19.9	24.0	24.1
11	20.6	20.7	25.1	25.4
12	21.2	21.7	26.0	26.7

Twenty-five female and 30 male non-obese children (6 - 12 years of age) of normal body mass and with no other musculoskeletal pathologies were selected from the same three venues. The number of non-obese subjects represented all consenting 6 to 12 year old children at the three venues according to the BMI criteria of Cole *et al.* (2000). All subjects were screened (see Section 3.1.2) before participating to ensure they satisfied the subject selection criteria. From the 55 non-obese subjects, 10 children matched to the 10 obese children, according to height, gender and age, were identified. The two groups were then compared to determine the effects of obesity on foot structure and function, foot sensation and plantar pressure distributions (see Section 3.1.1, 3.1.4 - 3.1.8).

Children 6 to 12 years of age were chosen for the study as development of the longitudinal arch of the foot is thought to have been completed by age 5 to 6 years (Staheli, 1987; Hennig *et al.*, 1994). Ten subjects per group was deemed sufficient to demonstrate a significant difference between the two groups based on calculations of statistical power (80%; Bach *et al.*, 1989) using mean and standard deviation data of a previous research study (Dowling *et al.*, 2001).

All subjects were aware of the research procedures, having received and understood a Subject Information Package (see Appendix 1 and 2) before testing. Parental consent and individual child consent was required before any subject was able to participate in this study (see Appendix 3). Before commencing the study, all procedures and methods were approved by the University of Wollongong Human Research Ethics Committee (see Appendix 4) and each testing venue (see Appendix 5 and 6).

3.0.1 Subject Recruitment

Subjects from Kinross Wolaroi Preparatory School were recruited by distributing Subject Information Packages and Informed Consent forms to all children who were 6 to 12 years old via the classroom teachers. The study was also advertised in the School Newsletter. Consent forms were returned directly to the classroom teachers. Prior to testing at Kidfit, subjects in the specified age group were identified through consultation with the Exercise Scientist-Manager. The children's parents were then contacted, either personally at the center or via letter and consenting subjects were then tested at individual appointment times. Subjects were recruited from Kids Uni by distributing Subject Information Packages and Informed Consent forms to the parents who had children in the 6 to 12 years old category.

3.1 Data Collection Procedures

3.1.1 Podiatric Assessment

Each of the subject's feet were assessed before testing to identify any abnormalities on the plantar surface of their feet, such as calluses and corns, which could affect later plantar pressure measurements. If abnormalities were found they were noted and plantar pressure measurements were examined carefully. These regions of high pressure and forces were then discarded during analysis.

3.1.2 Anthropometric Data Collection

The height of each subject was measured to the nearest millimetre using a portable, calibrated Hadlands Photonics (Glen Waverly, Victoria, Australia) stadiometer while the subjects stood barefoot in the anatomical position. Before each measurement was taken the subject was lifted vertically under the arms and then under the mandible in order to stretch the vertebral column and account for gravitational compression. A spirit level was attached to the arm of the stadiometer to ensure consistent arm alignment and therefore greater accuracy in height measurements.

Body mass was measured to the nearest 0.05 kg using a calibrated Precision Medical Scales (Tokyo, Japan; capacity 150 kg) while the subjects stood motionless and wearing minimal clothing (a T-shirt and shorts or skirt). Height and mass data were recorded three times each and the average values were later used to calculate each subject's BMI (see Section 3.2.1).

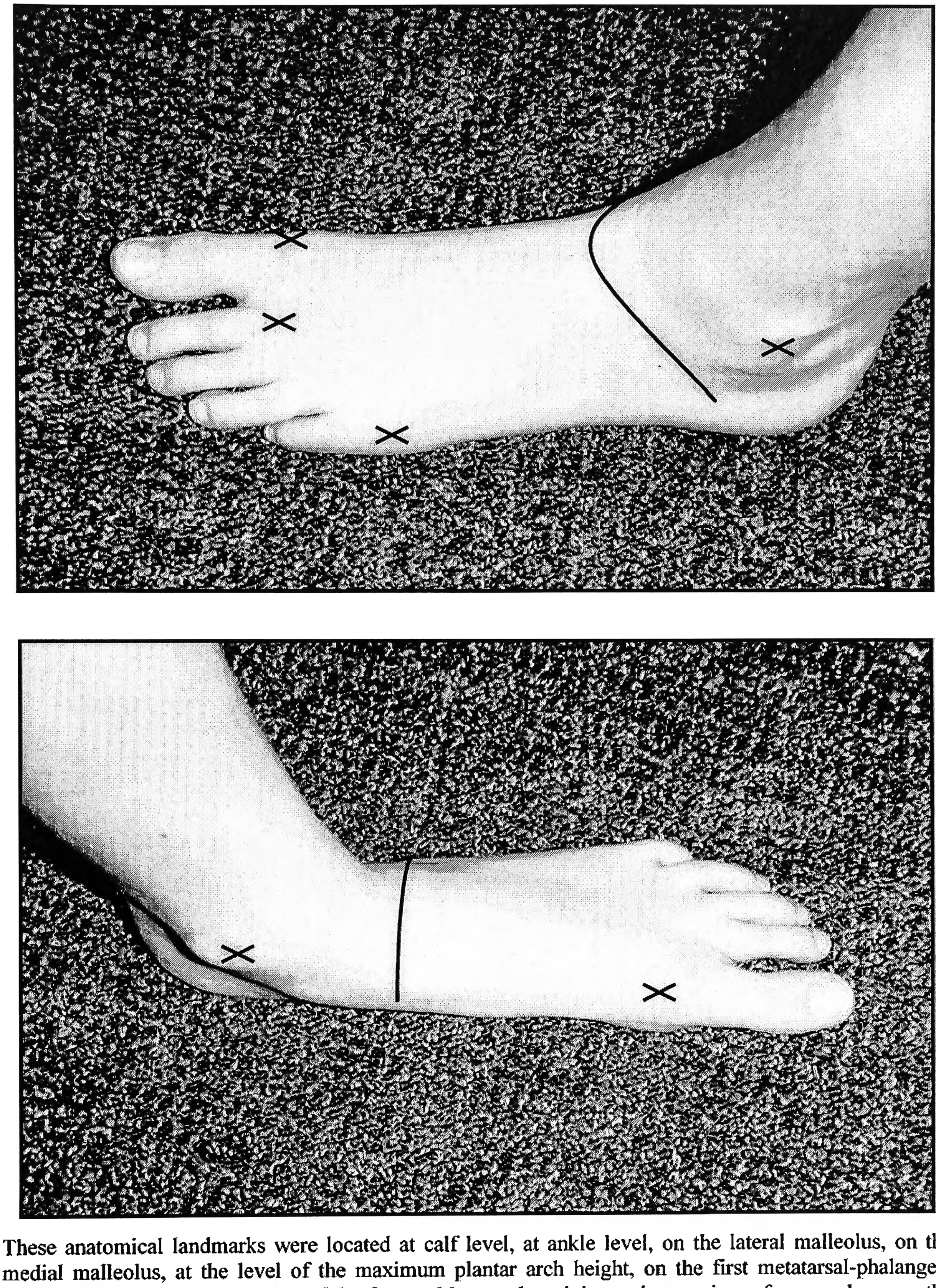
3.1.3 Foot Anthropometry Data Collection

Fifty-two foot dimensions, 26 per limb, were measured and recorded in order to determine differences in the external structural characteristics of the feet of the obese and non-obese children (see Table 3.2). Anatomical landmarks were firstly identified and marked on both limbs of each subject in order to serve as reference markers for the anthropometric measurements (see Figure 3.1 and Appendix 7; Parham *et al.*, 1992).

Table 3.2 Anthropometric foot measurements.

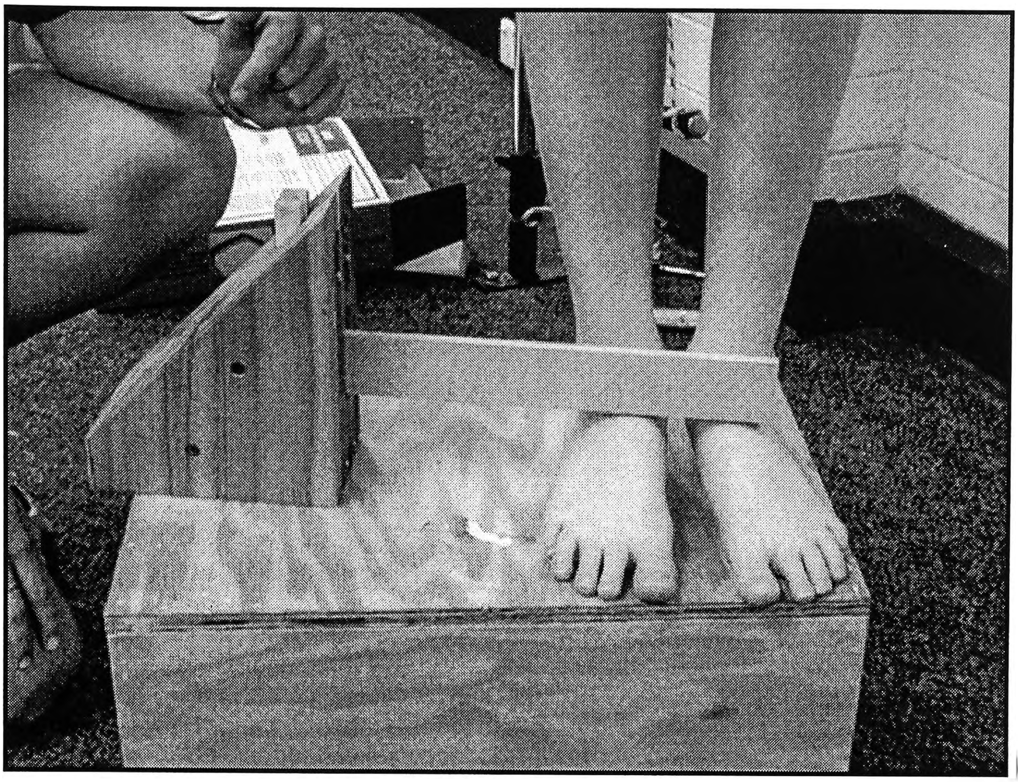
Variables	
(1) Calf Height	**(14)** Plantar Arch Height
(2) Ankle Height	**(15)** Ball of Foot Height
(3) Medial Malleolus Height	**(16)** 1st Toe Height
(4) Lateral Malleolus Height	**(17)** Maximum Toe Height
(5) Bimalleolar Breadth	**(18)** Outside Ball of Foot Height
(6) Heel Breadth	**(19)** Ankle Length
(7) Ball of Foot Diagonal Breadth	**(20)** Instep Length
(8) Calf Circumference	**(21)** Ball of Foot Length
(9) Ankle Circumference	**(22)** Foot Length
(10) Heel-Ankle Circumference	**(23)** Ball of Foot Breadth Horizontal
(11) Instep Circumference	**(24)** Outside Ball of Foot Length
(12) Ball of Foot Circumference	**(25)** 5th Toe Length
(13) Dorsal Arch Height	**(26)** 1st - 3rd Toes Breadth

The measurements were recorded with the subjects standing erect, eyes looking forward and feet approximately 10 cm apart or together, depending on the measurement, and following the specific protocols described by Parham *et al.* (1992). To ensure reliability and accuracy the chief investigator measured the anthropometric data from all the subjects. Each foot anthropometric variable was recorded three times to ensure accuracy and the average values were later used in the statistical analysis.

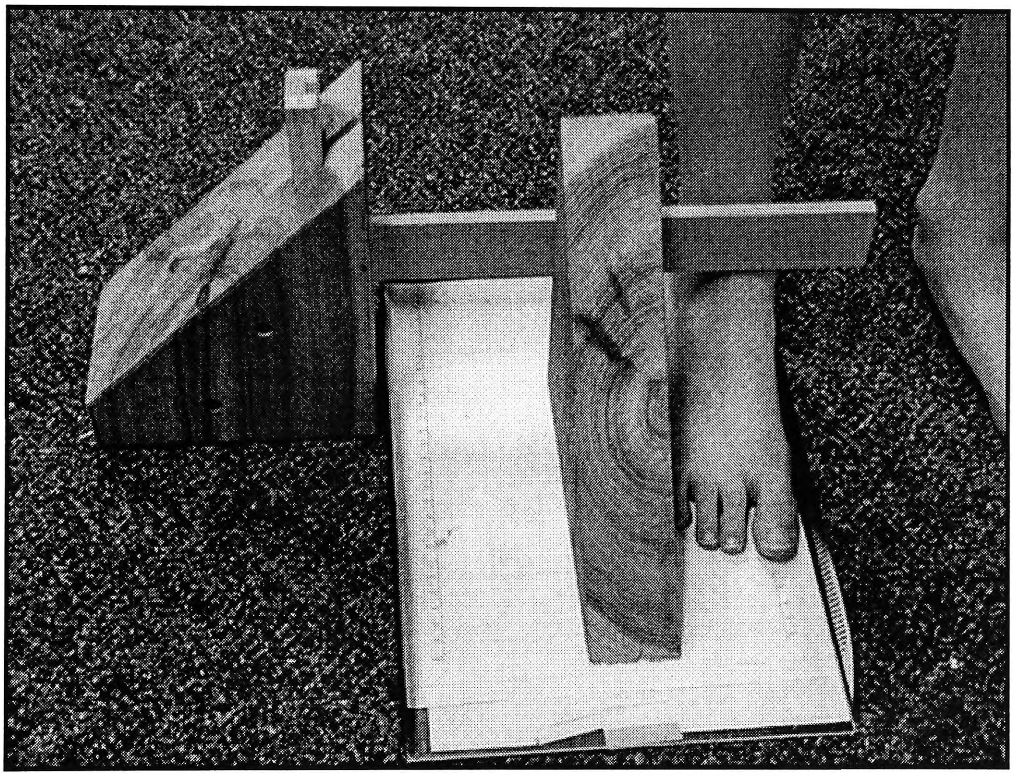


These anatomical landmarks were located at calf level, at ankle level, on the lateral malleolus, on the medial malleolus, at the level of the maximum plantar arch height, on the first metatarsal-phalangeal protrusion, at the dorsal junction of the foot and leg, at the minimum instep circumference plane, on the fifth metatarsal-phalangeal protrusion and at the maximum toe height location (see Appendix 7).

Figure 3.1 Anthropometric landmarks from which the anthropometric foot measurements were recorded (calf level and ankle level not shown).



(A)



(B)

Note: The equipment seen above; the adjustable wooden block, the wood block and the footboard, were custom made according to the requirements noted in Parham *et al.* (1992).

Figure 3.2 Anthropometric measurements: (A) dorsal arch height; and (B) ankle length.

Reliability studies were undertaken before commencing data collection to ensure results were repeatable. The chief investigator conducted three trials for each of the anthropometric variables on three consecutive days for 6 subjects. Intraclass Correlation Coefficients (ICC, Vincent, 1995) ranged from $R_1 = 0.8747$ to 0.99998 for the 54 anthropometric variables (See Appendix 8 for individual R_1 values). Therefore, the data were considered highly repeatable. During the study, the same tester was involved and the same apparatus and procedures were followed throughout testing in order to ensure reliability of the data collected.

3.1.4 <u>Footprint Data Collection</u>

The contact area of the plantar surface of the foot with the ground and characteristics of the longitudinal arch were determined through recording each subject's footprints. Footprints are recognised as a reliable, easily measured, inexpensive, and non-invasive method to characterise these external characteristics of the foot and which are appropriate for large subject numbers in a field study (Rogers, 1932 cited in Hawes *et al.*, 1992). Footprints of the subjects were taken using a Productos Suavepie (Spain) pedograph which was positioned on a level floor surface (Riddiford-Harland *et al.*, 2001; Dowling *et al*, 2001). The under side surface of the membrane was inked before each testing session and re-inked subsequently after every five subjects or when deemed necessary. The pedograph paper, clearly identified with the subject code, was placed beneath the inked membrane and the membrane was lowered into place. Footprints were taken for 2 seconds while the subject was standing in a weight bearing anatomical position, eyes looking forward at a fixed point 1 m away (see Figure 3.3). The test foot was assisted in being lowered both onto and away from the membrane. Two footprints were recorded for the left and right foot of each subject.

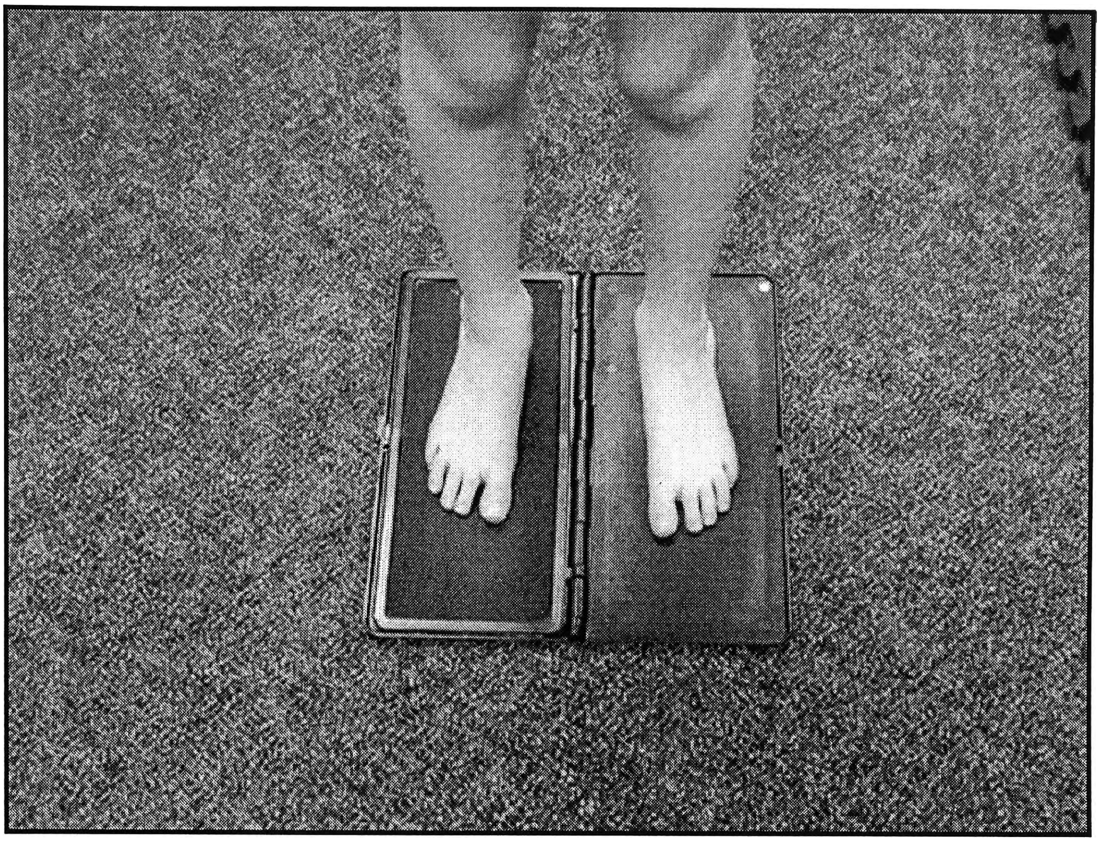


Figure 3.3 Method of footprint data collection.

3.1.5 Foot Sensation Assessment

Foot sensation for each subject was assessed to determine whether there were any differences between the two subject groups with respect to vibration and pressure responses. Vibration responses were tested using a 128 Hz sinusoidal oscillating Rydel-Seiffer tuning fork (Allied Health Industries, Melbourne, Australia) on 13 locations on the plantar surface of the foot; the hallux, all toes, five metatarsal heads, lateral and medial midfoot and heel (Figure 3.4). This method tests large nerve fibres and stimulates Pacinian corpuscles (Dons, 1992; Donaghue *et al.*, 1995). The tuning fork, once vibrating, was rested on the specific sites with a defined constant load (PNA, 1993). Placement of the fork on these locations was repeated three times, and the subject was required to perceive the sensation for 80% of the trials for a positive result to have been recorded. If the stimulus was not detected anywhere it was classified as absent and if it was not sensed at a single site it was termed to be a reduced threshold detected (Ziegler *et al.*, 1988; Masson *et al.*, 1989; Tsigos *et al.*, 1992; PNA, 1993).

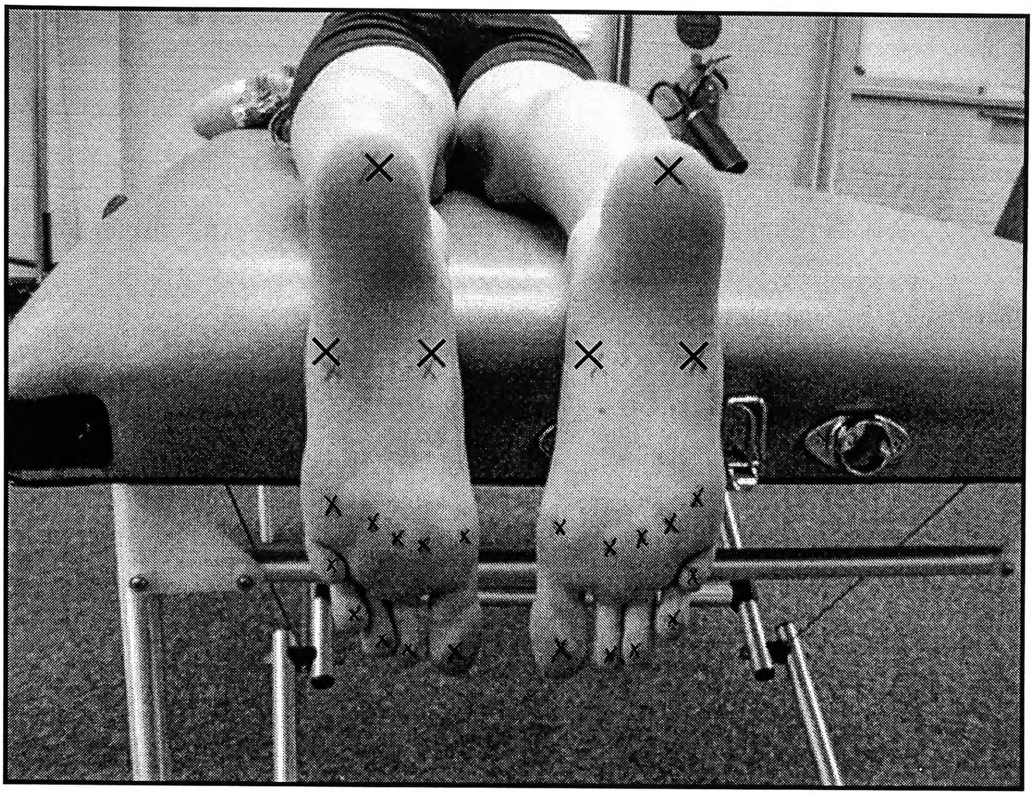
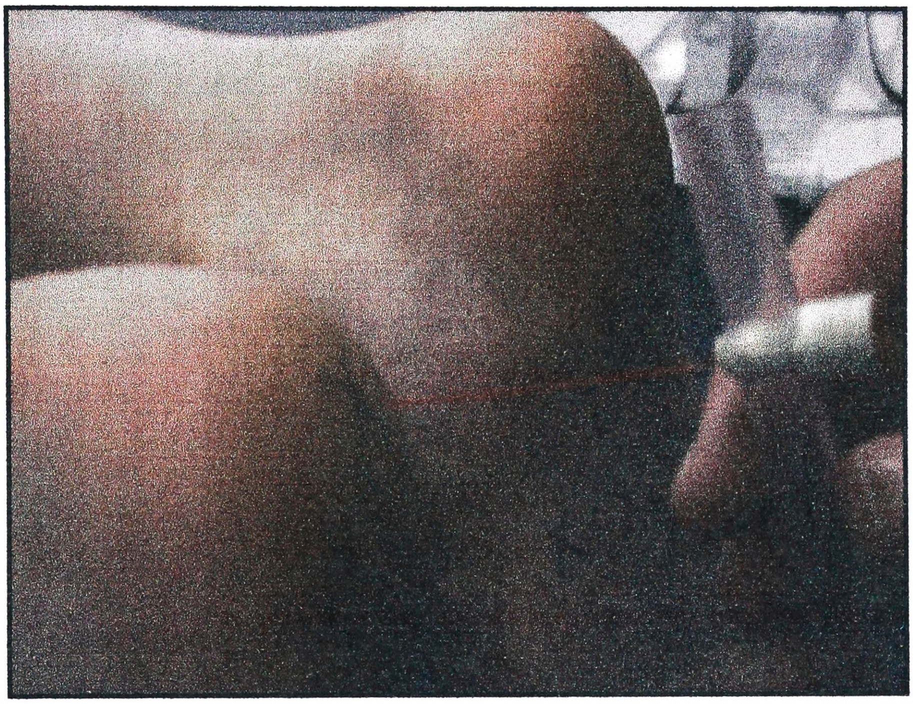
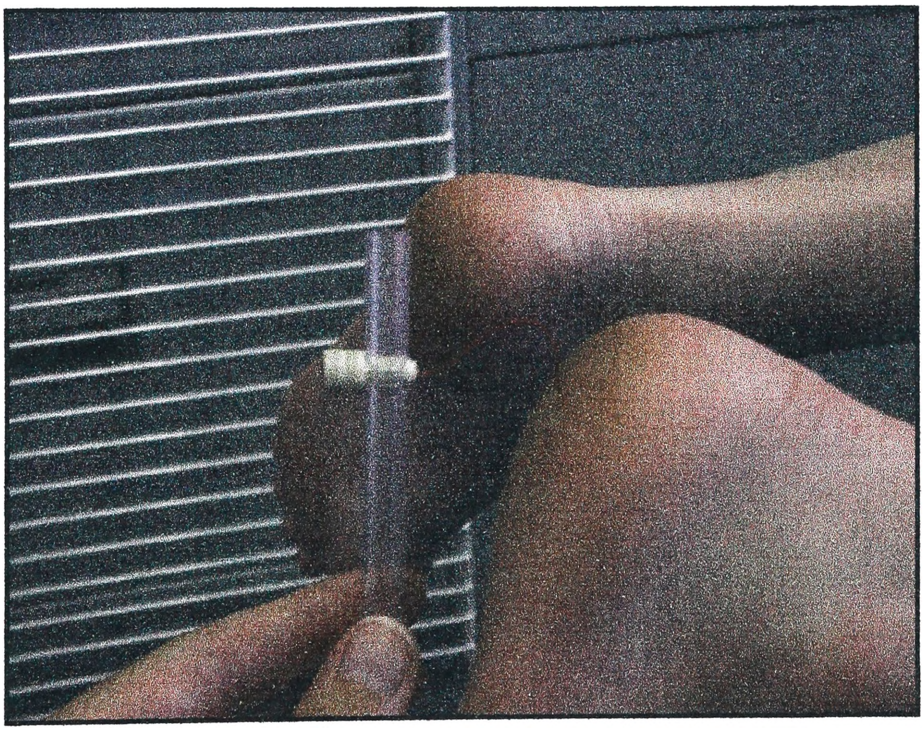


Figure 3.4 Anatomical sites for the vibration and pressure stimuli (adapted from Zangaro *et al.*, 1988).

Pressure sensation was tested using pre-calibrated Semmes-Weinstein nylon monofilaments (Brazil), an internationally accepted method to test pressure thresholds in differing areas of the foot. The use of monofilaments has been shown to be an excellent screening tool whereby the 5.07 monofilament has been identified as the best discriminator for risk of potential foot injury (Holewski *et al.*, 1988; Mueller *et al.*, 1989; Klenerman *et al.*, 1990). Each monofilament was applied to the plantar surface of each subject's foot, perpendicular to the skin for approximately 1 second (see Figure 3.5 (A)) with the aim of measuring each subject's ability to detect a point of pressure at specific sites (Zangaro & Hull, 1998). The force applied to the monofilament was the force required to bend the monofilament to form a 'C' (Birke & Sims, 1985; Holewski *et al.*, 1988; Zangaro & Hull, 1988; Mueller *et al.*, 1989; Dons, 1992; Simeone & Veves, 1997; Armstrong & Lavery, 1998; see Figure 3.5(B)). All of the monofilaments are of incrementing diameter and therefore the force required to achieve the 'C' shape and, in turn, the pressure applied to the plantar surface of the foot is incremental. These incremental values have been predetermined and calibrated, although they can also be calculated using a log10 function. The first monofilament (5.07) was applied to 13 pre-marked sites on the plantar surface of the foot, including all the toes, the five metatarsal heads, medial and lateral midfoot and the heel (Zangaro *et al.*, 1998; Nurse & Nigg, 1999; Figure 3.5) and repeated 5 times. These sites were randomly tested and required the subject to answer if they felt the stimuli. If the monofilament used was undetected, the next filament used was incremented and the same protocol was applied until the stimuli was sensed. This filament was recorded as characteristic of the subject's level of plantar pressure sensation.



(A)



(B)

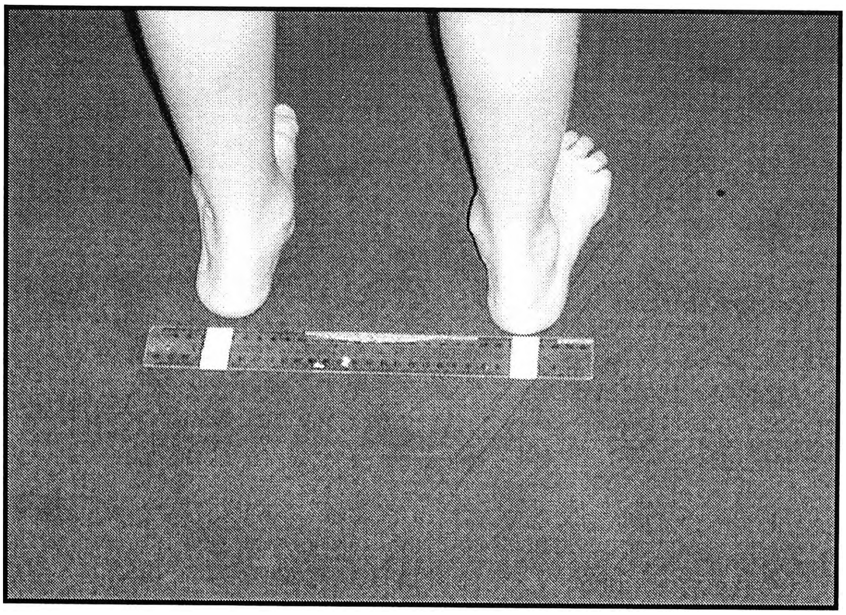
Figure 3.5 Semmes Weinstein monofilament test protocol: (A) straight monofilament; and (B) 'C' shape monofilament.

3.1.6 Joint Mobility Data Collection

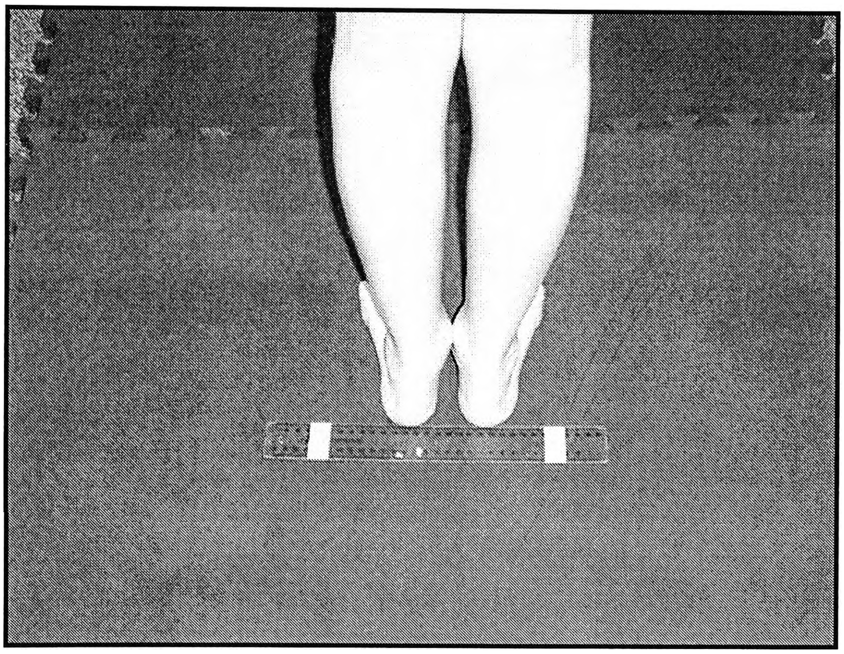
Range of motion of the talocrural joint was assessed in order to determine mobility between the talus, fibular and tibia. A goniometer was used to quantify the passive range of motion for plantar flexion and dorsiflexion for each subject following the procedures described by Norkin & White (1995; see Appendix 9). These measurements were assessed as previous research has shown that limited joint motion in the foot/ankle complex increases plantar pressures, therefore increasing the predisposition for foot ulcers in diabetic patients and may cause potential trauma in obese individuals (Delbridge *et al.*, 1988; Fernando *et al.*, 1991; Mueller *et al.*, 1994; Shaw & Boulton, 1997).

3.1.7 Rearfoot Alignment and Motion Data Collection

Alignment and motion of the rearfoot was videoed (Sony Digital Video Camera, Japan; 25 Hz) in the frontal plane for each subject statically and dynamically. The static rearfoot alignment had three conditions and included the children standing with their (1) heels together, (2) heels 20cm apart, and (3) heels comfortably apart (see Figure 3.6). The camera was positioned with the focal axis of the lens perpendicular to the horizontal axis of the pressure plate to minimise perspective errors. The camera was, on average, 1.9 m from the centre of the pressure plate and was placed on a 10 cm high box. To record rearfoot position, small spherical stickers (10 mm in diameter) were placed on each child's lower extremity during weight bearing, that is, the resting standing position (Cornwall & McPoil, 1995; Cornwall & McPoil, 1999). Marker placement was performed by bisecting the heel at 90 degrees to the floor; the first marker was placed at the distal posterior calcaneus, the second marker was placed on the proximal posterior calcaneus below the malleoli, the third marker was placed on the bisection of the Achilles tendon 5 cm above the malleoli and the fourth marker was placed on the bisection of the Achilles tendon 15 cm above the malleoli (Cailliet, 1985; Lundeen, 1985; Nigg, 1985; Sobel *et al.*, 1999; see Figure 3.7). The resting standing position was chosen in preference to the subtalar joint neutral position, a non-weight bearing alignment, as it is the weight bearing angle formed between the bisection of the Achilles tendon and posterior aspect of the heel that determines heel valgus and varus in a clinical setting (Fields & Craib, 1997; Marks & Schon, 1998; Sobel *et al.*, 1999).



(A)



(B)

Figure 3.6 Rearfoot positions: (A) heels 20 cm apart, and (B) heels together.

Although the foot is comprised of a rearfoot, midfoot and forefoot region, with these regions being involved together in supination and pronation of the foot complex, only two-dimensional rearfoot motion was investigated in the present study. Rearfoot motion was collected at the same time as the plantar pressure data in order for the pressure information to later be related to the stance phase of the gait cycle. The purpose of measuring rearfoot motion during the stance phase of the gait cycle was to determine if obesity affected basic functioning of the foot during one of the most common activities of daily living, walking. As rearfoot angle can be influenced by adipose tissue depositions in the thigh region, in turn, affecting when the heels will contact each other, it is possible that obesity will affect segmental motion and the way obese children walk. Rearfoot motion recorded in two dimensions has previously been found to be a reliable indicator of rearfoot function relative to a three-dimensional analysis for 6 to 60% of the stance phase (McPoil & Cornwall, 1994; Cornwall & McPoil, 1995; Cornwall & McPoil, 1999).

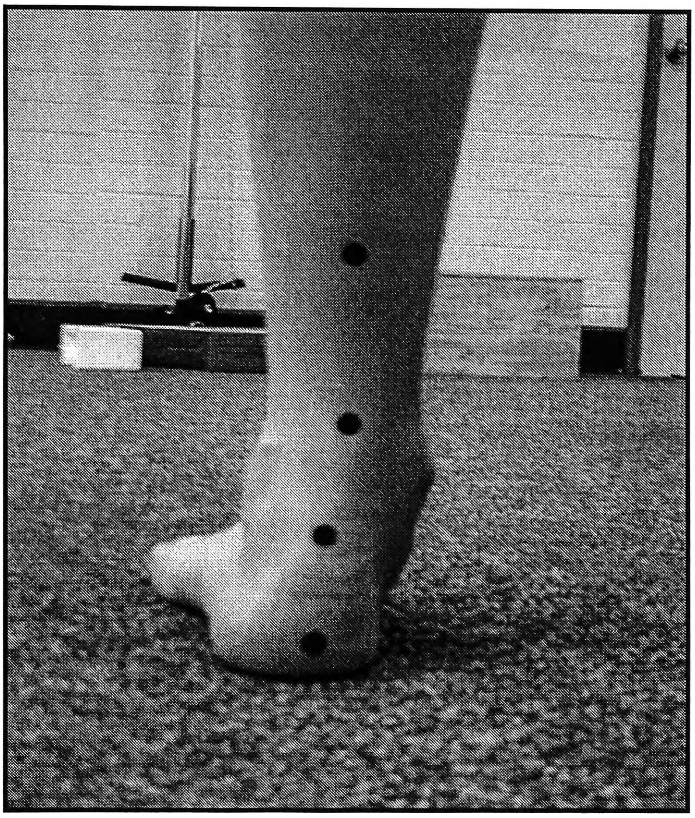


Figure 3.7 Rearfoot markers.

3.1.8 Plantar Pressure Distribution Data Collection

The AT-4 emed® system (Novel$_{gmbh}$, Munich) was used to quantify static and dynamic pressures generated on the plantar surface of the foot of each subject. The AT-4 emed® system consists of a plate (see Figure 3.8) connected directly to a laptop computer. Details pertaining to the design specifications of the AT-4 emed® system are included in Table 3.3. The system used capacitive sensors as were described in Section 2.5.

The AT-4 emed® platform was placed on a firm, level surface and then surrounded by a custom-designed walkway. The main requirements for the walkway included being lightweight, easily transportable, a comfortable surface for barefoot gait, long enough to conduct the dynamic trials, and a suitable thickness to ensure that the plate was flush with the surrounding walkway. After extensive pilot testing, interlocking high density foam squares were chosen as they provided sufficient density and protection for the plantar surface of the children's feet whilst closely fitting the other testing requirements (see Figure 3.9).

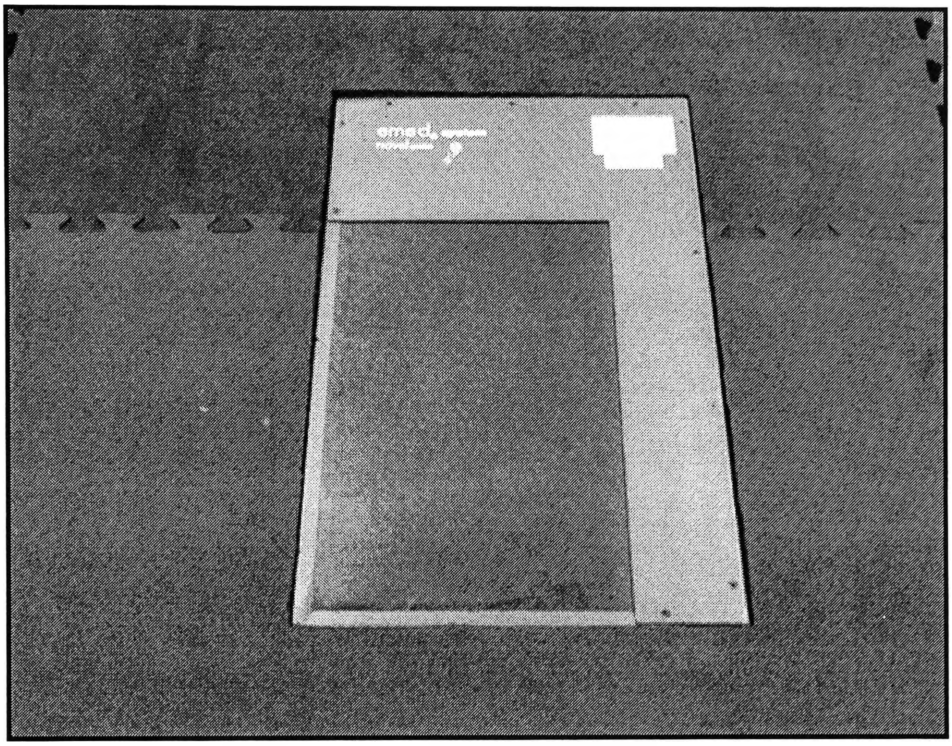


Figure 3.8 The AT-4 emed® system.

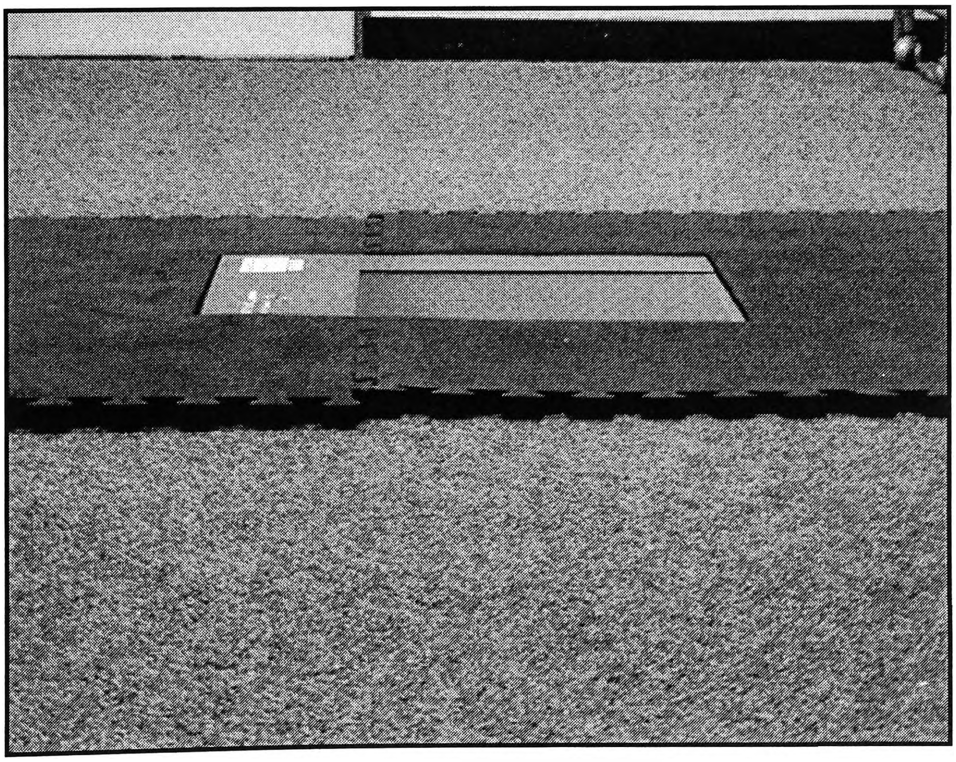


Figure 3.9 The custom built walkway.

Table 3.3 Design specifications of the AT-4 emed® platform.

Variables	Specifications
Dimensions	582 x 340 x 20 mm
Sensor Area	360 x 190 mm
No. of Sensors	2736
Resolution	$4/cm^2$
Frequency	25 Hz
Range	1-127 $N \cdot cm^{-2}$
Threshold	1 $N \cdot cm^{-2}$
Accuracy	7%
Hysteresis	<3%
Temp. Range	10 - 40 C
Max. Total Force	86900 N
Cross Talk	-40 db
Cable Length	3 m

3.1.8.1 Static Plantar Pressure Measurement

To assess static plantar pressure distribution, each subject stood relaxed in the anatomical position, looking forward at a picture of a smiling face on the wall, with one foot on the AT-4 emed® platform and mass evenly distributed on both feet (see Figure 3.10), for 5 seconds. Two static plantar pressure trials were recorded ($N \cdot cm^{-2}$) for each subject's left and right foot at 25 Hz*. The pressure data were collected using the Win Emed 1.18e program, and transferred directly to a Dell laptop computer where it was saved for later analysis. The threshold of the AT-4 emed® plate (1 $N \cdot cm^{-2}$) at which the plate was triggered to collect data was high relative to the mass of some of the smaller children, making static pressure data difficult to collect.

* 25 Hz is the maximum collection frequency of the AT-4 emed® platform.

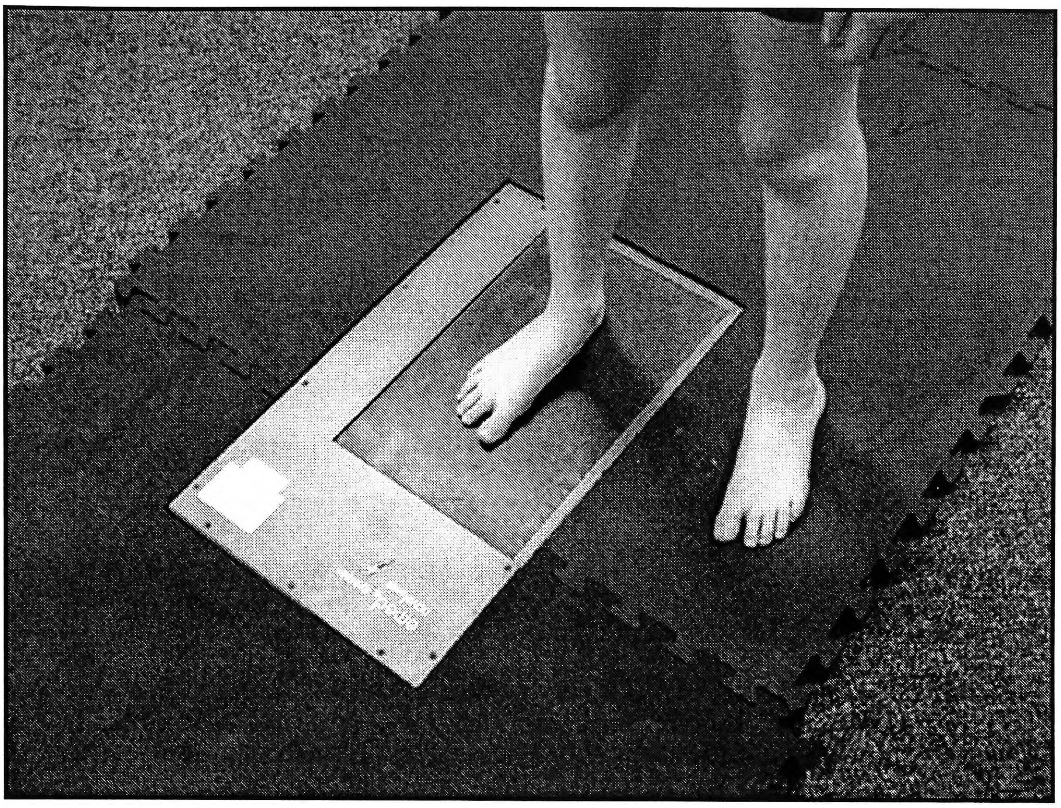


Figure 3.10 Static plantar pressure data collection using AT-4 emed® plate.

3.1.8.2 Dynamic Plantar Pressure Assessment

To assess dynamic plantar pressure distributions each subject walked over the AT-4 emed® platform at a consistent walking pace which was set by an accompanying walker's speed (Hennig *et al.*, 1998) and using the two-step method (Dowling *et al.* 2001). There are three different data collection methods recommended when using emed® platforms to assess dynamic plantar pressure during gait: (i) the mid-gait method, (ii) the two-step method and (iii) the one-step method (Meyers-Rice *et al.*, 1994; Bryant *et al.*, 1999). The two-step method has been shown to elicit peak pressure and vertical force values in the fore-, mid- and rearfoot areas, which are relatively representative of the pressures and vertical forces recorded during the traditional mid-gait method. In contrast, in the one-step method the peak vertical force has been shown to be radically different from the mid-gait method (Meyers-Rice *et al.*, 1994) and therefore was not used in the present study. For the two-step method, the subject stood approximately 1.2 m in front of the AT-4 emed® platform, stepped onto the platform with their second foot strike and continued to walk over and past the plate for approximately 2 m (see Figure 3.11). The two-step method was selected for use in preference to the one-step or mid-gait method (Hennig *et al.*, 1994; Bryant *et al.*, 1999;

Dowling *et al.*, 2001) as the young subjects tested in the present study had a better chance of striking the platform without the need for excessive repeated trials. The two-step method is relatively simple to perform and is preferable to use if subjects fatigue easily (Myers-Rice *et al.*, 1994).

Before data collection, each subject practised walking with the accompanying walker to become accustomed to the walking pace. An accompanying walker was used to guide the subjects during the dynamic trials in order for the subjects to walk at a consistent pace (Hennig, July 1998; personal communication; Dowling *et al.*, 2001; see Figure 3.11). Familiarisation trials were also performed to limit targeting of the pressure platform and to ensure that each child was comfortable with the experimental procedures. Data collection was restricted to five successful trials per foot for all subjects during the dynamic condition to minimise fatigue. Dynamic data were collected using a Dell laptop and stored for later analysis. Dynamic pressure measurements using the AT-4 emed® plate were triggered when the force generated by the first foot contact exceeded the threshold of 1 $N{\cdot}cm^{-2}$.

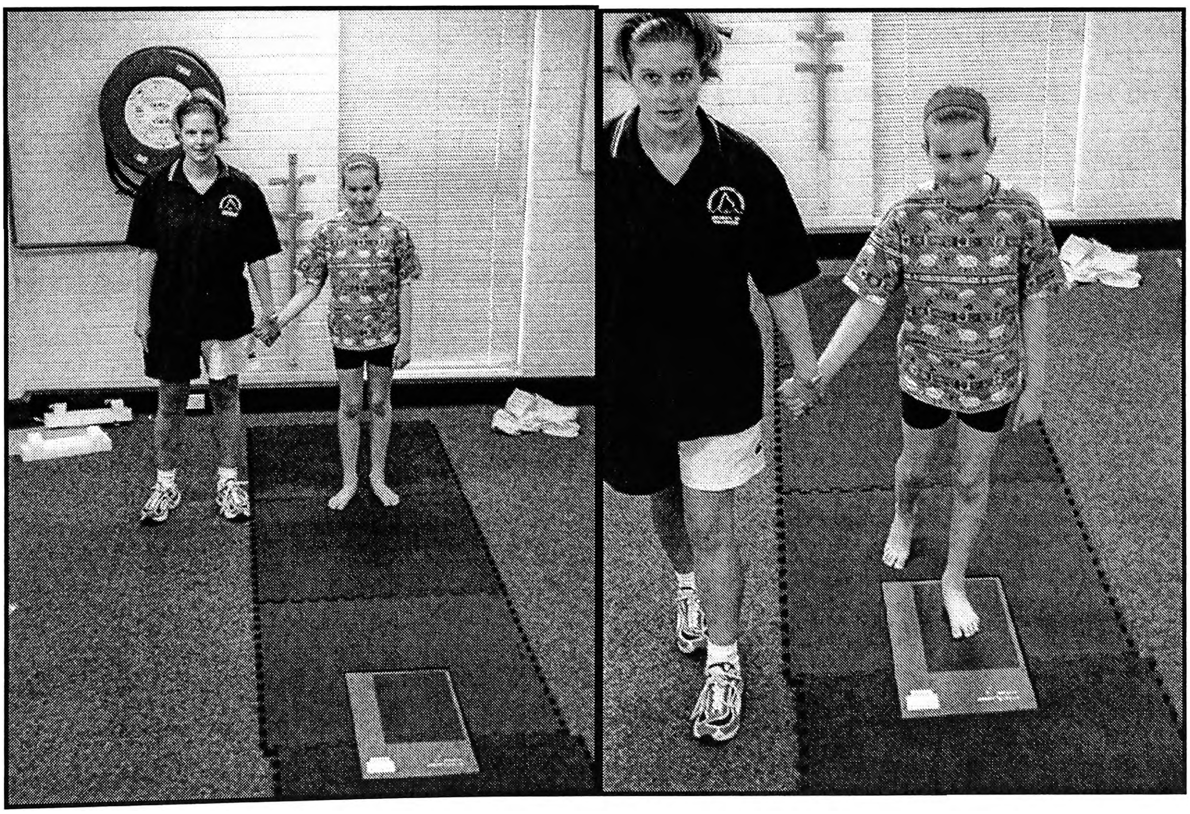


Figure 3.11 Dynamic plantar pressure data collection.

All static and dynamic plantar pressures ($N \cdot cm^{-2}$) were recorded with subjects barefoot, for each sensor on the AT-4 emed® plate using Novel® software packages. The purpose of assessing plantar pressure during static weight bearing and dynamic gait was to quantify the actual forces and pressures applied to each region of the plantar surface of the foot during the typical activities of daily living, standing and walking.

3.1.9 Data Collection Schedule and Testing Venues

Two testing venues were used to collect data for the study, (1) the Exercise Science Unit at the University of Wollongong, Wollongong, NSW, and (2) Kinross Wolaroi Preparatory School, Orange, NSW. On arrival at the test venue each subject's consent form was checked to ensure written parental and child consent and the objectives of the study were re-explained to the subject. The subject's shoes and socks were then removed and their clothing adjusted to ensure minimal additional mass (see Section 3.1.2). After washing and drying the children's feet, the sensory tests were conducted so that the results were not influenced by possible changes in foot temperature as consequence of the gait trials. Before the anthropometric measurements were recorded, the subjects were asked to practice toe raises in order to warm up the foot/ankle complex. After recording each subject's height and mass, and conducting the podiatric assessment, joint range of motion tests were conducted. The subject's footprints were then recorded using the pedograph, followed by the plantar pressure assessments on the AT-4 emed® plate, during which time the subjects were videotaped from the rear view and below hip level. The final data collection station was foot anthropometry. The subjects were able to rest at any time during the testing protocol to prevent fatigue. A summary of the data collection schedule is shown in Appendix 10. Testing took approximately 40 minutes per subject. At the end of the testing session all participants received a reward sticker and a certificate of participation (see Appendix 11).

3.2 Data Analysis

3.2.1 Anthropometric Data Analysis

Body Mass Index (BMI) was calculated using the Quetelet Index (see Equation 3.1) as an indicator of obesity (Dietz & Bellizzi, 1999).

$$BMI = \frac{\text{mass (kg)}}{\text{height}^2\text{ (m)}}$$ **Equation 3.1**

Body Mass Index was considered the most appropriate non-invasive method available for a field study to characterise obesity in children considering the time and financial constraints of the study, as it has been established as an adequate measure of adiposity (Flegal, 1993; Cole *et al.*, 2000). Subject's BMI data were classified according to the new international criteria to identify the subjects who were obese and non-obese (see Table 3.1: Cole *et al.*, 2000).

For each of the 52 foot anthropometric measures collected, the data were averaged across the three trials for each variable.

3.2.2 Footprint Data Analysis

One left and one right footprint obtained using the pedograph per subject was selected for analysis based on clarity and quality of the print. From these footprints, Footprint Angle (FA) and the Chippaux-Smirak Index (CSI) were calculated following the protocol described by Forriol & Pascual (1990; see Figure 3.12).

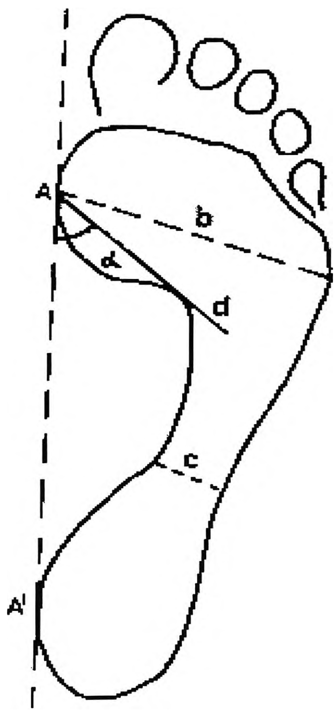


Figure 3.12 Footprint parameters. α: FA, c and b%: CSI (Forriol & Pascual, 1990, p 102).

In order to obtain FA, a straight line was drawn (A-A') connecting the most medial points at the forefoot and heel. Another line was drawn (A-d) from point A to the apex of the concavity of the medial longitudinal arch (d). The resultant angle, α, thereby represented FA. The CSI was calculated by drawing a line from point A across the widest section of the forefoot (b). A second line (c) was drawn parallel to line b to identify the narrowest section of the medial longitudinal arch. These two lines were measured and then the CSI was calculated using Equation 3.2.

$$\text{CSI (\%)} = \frac{\text{line c}}{\text{line b}} \times 100$$ **Equation 3.2**

The FA and CSI values were then classified according to the specifications of Forriol & Pascual (1990) as listed in Table 3.4. The purpose of the footprint analysis was to quantify the surface area of each child's foot that was in contact with the ground during static weight bearing and to quantify external characteristics of their medial longitudinal arch. The assumption made with FA is that as the arch becomes higher the arch angle should therefore increase.

Table 3.4 Classification of FA and CSI (Forriol & Pascual, 1990).

Group	**FA (°)**	**Description**
I	0-29.9	Flatfoot
II	30-34.9	Lowered arch
III	35-41.9	Intermediate arch
IV	>42	Normal foot
Category	**CSI (%)**	**Description**
I	0	High arch foot
II	0.1-29.9	Normal foot
III	30-39.9	Intermediate foot
IV	40-44.9	Lowered arch
V	>45	Flat arch foot

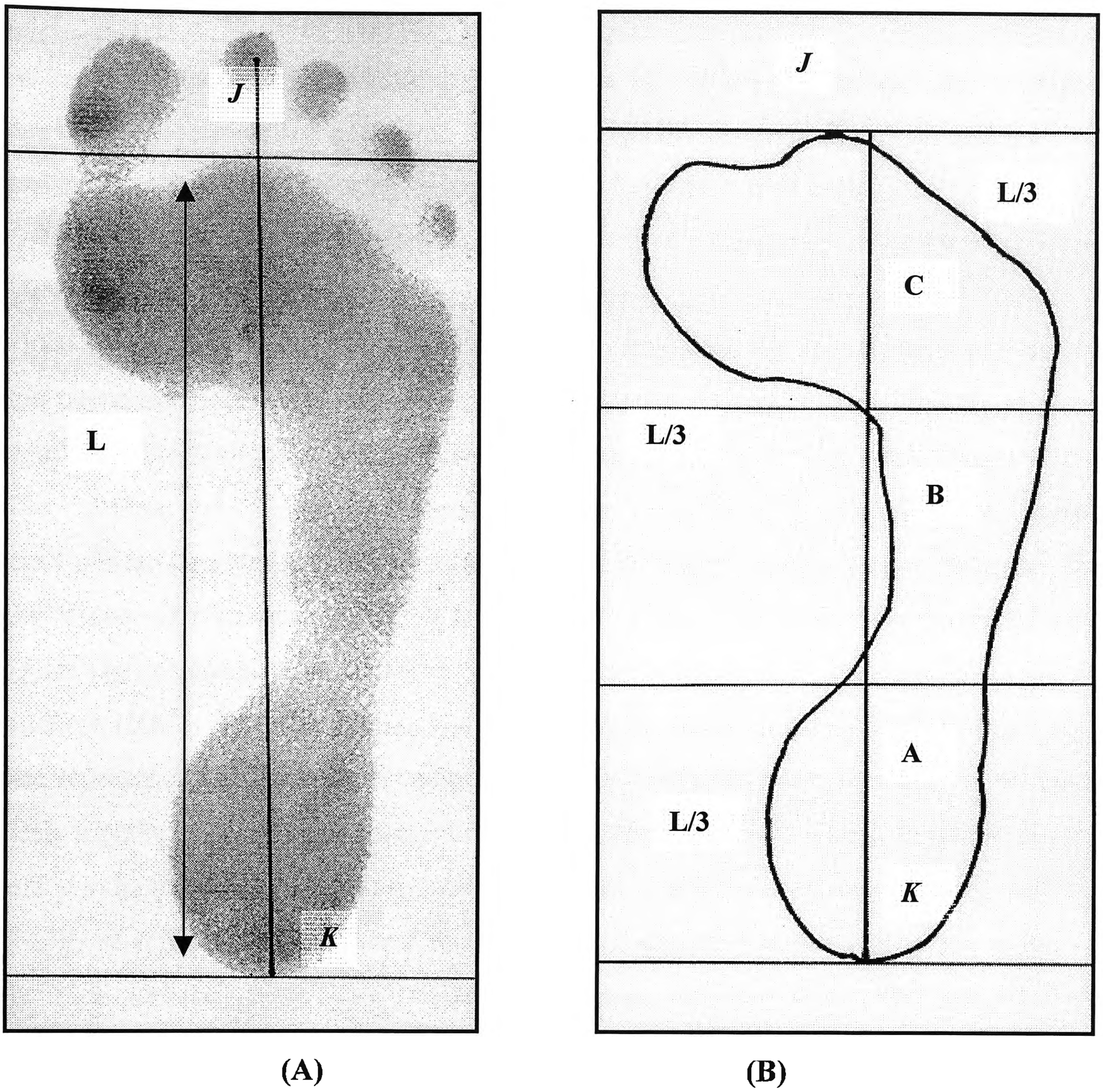
Arch Index (AI) was also quantified as an indicator of longitudinal arch height. Although the AI can be calculated both statically and dynamically, it was only analysed in the static condition in this study (Cavanagh & Rodgers, 1987). Each subject's footprints were scanned using a 5p Scanjet optical scanner and digitised with Sigmascan v 3.0 (Jandel Scientific, 1996) to determine AI. A line *JK* was drawn through the centre of the heel *K* to the tip of the 2nd toe to represent the foot axis on the digitised print of the inked footprint. A perpendicular line was then drawn at the most anterior part of the outline of the body of the print in front of the metatarsal heads. The point where these two lines intersect is at point *J* on the line *JK*. The main body of the footprint was then divided equally into three parts; A (rearfoot), B (midfoot), and C (forefoot). Arch Index was then calculated using the total area of the footprint A + B + C, the midfoot area B, and using Equation 3.3 (Cavanagh & Rodgers, 1987; Hawes *et al.*, 1992, see Figure 3.13).

$$\text{Arch Index} = \frac{B}{A + B + C} \qquad \textbf{Equation 3.3}$$

The AI values were then classified according to high arch, normal and flat arch criteria (Table 3.5).

Table 3.5 Classification of the Arch Index (Cavanagh & Rogers, 1987).

Description	**Index**
High Arch	$AI \leq 0.21$
Normal	$0.21 < AI < 0.26$
Flat Arch	$AI \geq 0.26$



(A) The footprint is taken with pedograph ink and paper. The points *JK* are identified as in the text. (B) The outline of the footprint, excluding the toes, is digitised. It is then divided into equal thirds by parallel lines which are perpendicular to the line *JK*. The arch index (AI) is calculated as the ratio of the midfoot area (B) to the total area of the foot excluding the toes (A+B+C).

Figure 3.13 The divisions of the Arch Index (adapted from Cavanagh & Rodgers, 1987, p 548).

3.2.3 <u>Foot Sensation Data Analysis</u>

Verbal responses to the sensory stimuli were coded as a positive or negative response for vibration. For pressure, verbal responses to the sensory stimuli were coded as a positive or negative response according to the monofilament detected.

3.2.4 Range of Motion, Rearfoot Alignment and Rearfoot Motion Data Analysis

For both plantar flexion and dorsiflexion range of motion the values were averaged across the three trials for each limb for each subject. Rearfoot alignment and rearfoot motion were then calculated following the procedures described below.

3.2.4.1 Data Capture and Digitising Procedures

Video images of rearfoot alignment and motion displayed by the 10 obese and the 10 non-obese subjects were initially visually inspected and trials with all four markers clearly visible throughout the tasks were selected for analysis. The video images of the selected trials were digitally transferred from the Sony TRV-230 video recorder (Japan) to a Compaq Pentium II personal computer via a DVRaptor video capture card using the DV Video software package into a Microsoft AVI file. The image was displayed on a 43 cm Optima colour monitor for digitising using the Hu-m-an™ (version 3.0) software package (HMA Technology Inc, Canada). For the static trials of rearfoot alignment, one representative frame from each of the three conditions were selected for analysis; heels together, heels 20 cm apart, and heels comfortably apart. The co-ordinate data (x and y values) of the lower limb landmarks (heel, calcaneus, Achilles tendon, calf and two fixed reference points) were then manually digitised following the same sequence for each representative frame. For the dynamic analysis of rearfoot motion three representative trials were selected. The co-ordinate data (x and y values) of the lower limb landmarks (heel, calcaneus, Achilles tendon, calf and two fixed reference points) were then manually digitised following the same sequence for each frame (25 Hz). Digitising commenced at least five frames before heel strike in the dynamic movement to at least five frames after midstance.

Two fixed reference points, immovable markers located on the corners of the emed AT-4 plate, were digitised as horizontal reference points. The digitised data was then smoothed using a second order two-pass Butterworth filter with a cut-off frequency of 6 Hz (Winter, 1990).

3.2.4.2 Reliability of the Digitising Procedure

To ensure reliability of the digitised data, the entire digitising procedure was completed before digitising the data. Six sets of data (consisting of 30 frames each) were digitised on three consecutive days to assess reproducibility of the digitising procedures. An ICC of R_1 = 0.9962465 was calculated indicating a high correlation between data sets (Vincent, 1995).

To assess the accuracy of the digitising system, 10 defined points were marked on the digitising screen. These points were then digitised 5 times with co-ordinate reproduction within +/- 3 pixels. An ICC of R_1 = 0.999996 was also calculated indicated the digitising system produced accurate and reliable data.

3.2.4.3 Markers

Possible marker movement during the dynamic trials was noted as a limitation of this study, although the markers were placed on the less fleshy regions of the lower limb (Laviolette & Pierrynowski, 1988; Lamoreux, 1991). Furthermore, as the movement was relatively slow and produced limited segmental twisting of the lower limb, marker movement was not deemed a major problem.

The variables selected for analysis included: (1) rearfoot angle at initial foot-ground contact, (2) Achilles tendon angle at initial contact, (3) rearfoot angle at midstance, (4) Achilles tendon angle at midstance, (5) the change in rearfoot angle between midstance and initial contact and (6) the change in Achilles tendon angle between midstance and initial contact (°). Drawing lines through the bisection of the heel markers and the horizontal calculated rearfoot angle. The angle C between these lines was rearfoot angle (see Figure 3.14). A line was drawn through the bisection of the Achilles tendon markers and through the heel bisection markers. The Achilles tendon angle, angle B, was calculated from these lines (see Figure 3.14). Data obtained for each subject's left limb were corrected so that it was comparable with their right limb data.

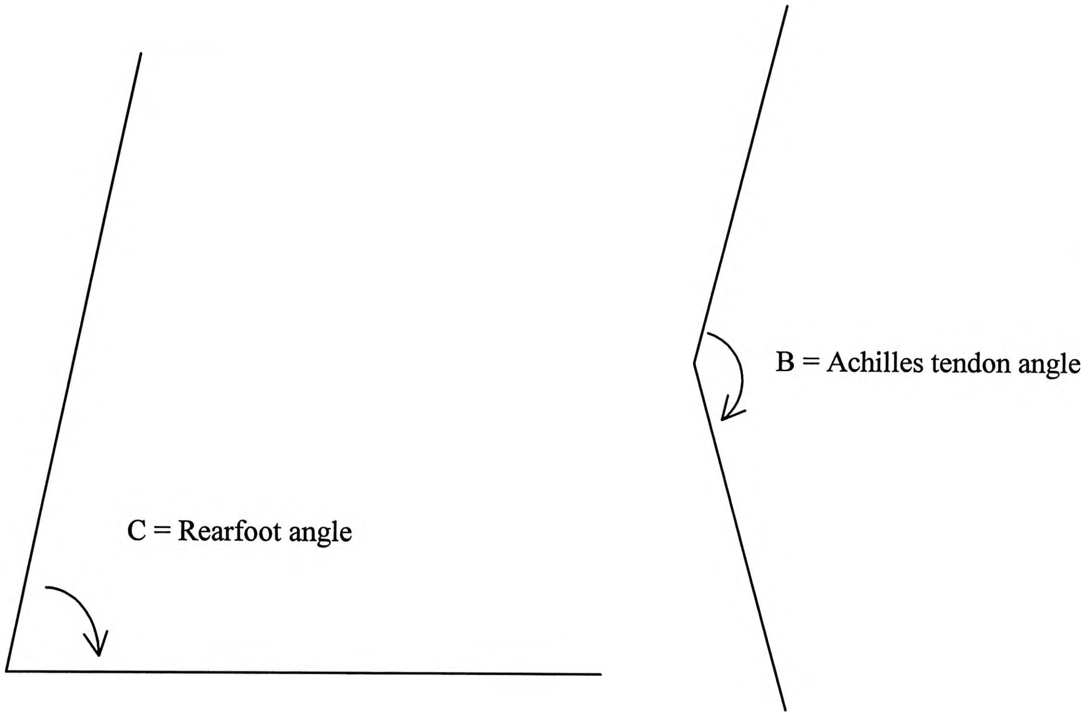


Figure 3.14 Schematic representation of rearfoot angle and Achilles tendon angle.

3.2.5 Plantar Pressure Distribution Data Analysis

For the static plantar pressure measurements the variables of peak force, peak area and peak pressure for the total foot were initially determined using the Novel® emed-SF® software. For the dynamic plantar pressure measurements each footprint was initially divided into two anatomical regions; the forefoot (as defined by the Novel® emed-SF® software which automatically was set at 50% of the length of the footprint) and rearfoot. Peak force, peak area and peak pressure were then derived for the total foot and for the two foot divisions using the Novel® emed-SF® software. Peak pressures were selected for analysis in the present study as peak pressures reveal information about the pressures imposed on the foot at any stage during contact with the plate (Hennig *et al.*, 1994). Values of peak pressures and relative forces were averaged across the five trials collected for each foot during each condition before further statistical analysis. The purpose of this section of the plantar pressure analysis was to replicate the procedures employed by Dowling *et al.* (2001), thereby enabling direct between-study comparisons.

The foot was then divided into discrete regions using the Peter Cavanagh 10 mask set and following the anatomical landmarks on the foot: medial and lateral heel, medial and lateral midfoot, metatarsal head (MTH) 1, MTH 2, MTH 3-5, hallux, 2^{nd} toe, toes 3-5 (Cavanagh *et al.*, 1987; Novel® automask; see Figure 3.15). A pre-determined toe algorithm was also used in all of the emed prints for a more correct representation of the toes (Novel® automask). Once all footprints had been masked they were further analysed using Novel® multimask to determine the following variables for each of the 10 masks: peak area, pressure and force, instant of the roll-over process at which peak pressure and peak force occurred, contact time, pressure-time integrals and force-time integrals. Analysis of the peak force, area and pressure in each mask enabled location of specific sites on the foot, which were exposed to high loading. Contact time analysis allowed the time that each individual mask was in contact with the platform to be calculated. Pressure-time integrals were selected for analysis as they provide vital information pertaining to the integrity of the skin whereas force-time integrals assist in evaluating the effects of fatigue on bone (Fuller, 1996).

Figure 3.15 A footprint displaying the ten masks.

3.3 Statistical Analysis

3.3.1 The Dependent Variables

The dependent variables analysed in the study are listed in Table 3.6.

Table 3.6 The dependent variables used for statistical analyses.

Methods	**Dependent Variables**
1. Foot Anthropometry	* 26 per limb
2. Pedograph Footprint	* FA(°)
	* CSI (%)
	*AI
3. Sensory Foot Function	* Vibration measurement
	* Pressure measurement
4. Joint Motion	* Dorsiflexion (°)
	* Plantar flexion (°)
5. Rearfoot Motion	**Static Alignment**
	* Rearfoot angle (°)
	* Achilles tendon angle (°)
	Dynamic
	* Rearfoot angle (°)
	* Achilles tendon angle (°)
6. Static Plantar Pressure	* Peak force (N)
	* Peak area (cm^2),
	* Peak pressure ($N \cdot cm^{-2}$),
7. Dynamic Plantar Pressure	For the total foot, rearfoot, forefoot and 10 mask areas the following variables were calculated:
	* Peak force (N)
	* Peak area (cm^2),
	* Peak pressure ($N \cdot cm^{-2}$),
	Other variables included:
	* % of roll-over-process
	* Pressure-time integrals
	* Force-Time Integrals

3.3.2 Characteristics of the Sample

To describe the physical characteristics of the obese and non-obese subjects, means and standard deviations were calculated for the variables of age, height, mass and BMI. These variables were then analysed using independent *t*-tests to determine whether there were any significant differences between the non-obese (n = 10) and obese (n = 10) children.

3.3.3 Anthropometric Measurements, Joint Motion, Footprint Data and, Static and Dynamic Pressure Data

Means and standard deviations were calculated for the two groups for the dependent variables. Prior to analysis, a Kolmogorov-Smiranov test (with Lillefors' correction) was used to test data for normality. A two-way analysis of variance (ANOVA) design with one between factor (body type: obese and non-obese) and one within factor (test limb: left and right) was conducted to determine whether there were any significant main effects of either test limb or obesity ($p < 0.05$) on the variables. When a main effect in body type or test limb was demonstrated, *post hoc* comparisons of the means were conducted using a Tukey HSD test.

3.3.4 Foot Sensation Data

Means and standard deviations were calculated for the two groups for the dependent variables of pressure and vibration. A Mann-Whitney Rank Sum test was performed on the ranks to determine the level at which the stimuli were felt. The purpose of this analysis was to determine whether there was an effect of obesity on the variables characterising foot sensation.

3.3.5 Rearfoot Motion Data

Means and standard deviations were calculated for the two subject groups for the dependent variables of rearfoot angle and Achilles angle derived from the digitised video data for the left and right foot. Prior to analysis, a Kolmogorov-Smiranov test (with Lillefors' correction) was used to the test data for normality. For the static rearfoot alignment data a three-way ANOVA was performed with one between factor (body type: obese and non-obese), and two within factors (limb: left and right; stance: together, 20cm apart, comfortable) to determine whether there were any main effects of test limb, stance or obesity on rearfoot alignment. For the dynamic rearfoot motion data a two-way ANOVA design was performed with one within factor (limb: left and right) and one between factor (body type: obese and non-obese) for the dependent variables of rearfoot angle and Achilles angle at initial contact and midstance. When a main effect of body type or limb was demonstrated, *post hoc* comparisons of the means were conducted using a Tukey HSD test.

All statistical analyses were conducted using Jandel SigmaStat® 2.0 software on a Pentium computer. A level of significance of $p \leq 0.05$ was selected in all analyses to limit the chance of a Type I error to 5%.

Chapter 4

Results & Discussion

4.0 Characteristics of the Sample

Descriptive and statistical data describing the 10 obese (4 female and 6 male) subjects and the 10 non-obese subjects, matched to the obese children for age, height and gender are outlined in Table 4.1. There were no significant differences between the two subject groups for either age or height, confirming appropriate matching of the subjects on these criteria. However, as anticipated there were significant differences between the non-obese and obese subjects for both mass and BMI (see Table 4.1). Furthermore, the mean BMI of the obese children was above the mean BMI for obese children in this specific age group (22.8 kg/m^2; see Table 3.1) as reported by Cole *et al.* (2000). In contrast, the mean BMI of the present non-obese children was only 16.83 and therefore, the subject groups were considered to truly represent both obese and non-obese children.

Table 4.1 Age, height, mass and BMI data for the non-obese (n = 10) and obese (n = 10) subjects.

	Non-obese		Obese		*t*-value	*p*-value
Variable	**Mean**	**SD**	**Mean**	**SD**		
Age (yrs)	8.9	2.1	8.8	2.0	0.107	0.916
Height (m)	1.38	0.13	1.42	0.11	-0.818	0.424
Mass (kg)	32.2	8.1	52.8	13.8	-4.085	<0.001*
BMI (kg/m^2)	16.83	1.98	25.78	3.76	-6.671	<0.001*

* Denotes significant difference at $p \leq 0.05$.

4.1 Foot Anthropometry Analyses

Descriptive statistics pertaining to the anthropometry of the right and left feet for the obese and non-obese groups are presented in Table 4.2. No studies could be located investigating foot anthropometry in children against which to compare the present findings. Two-way ANOVA results revealed no significant main effect of limb on any of the 26 dependent variables when the data were pooled across subject groups (see Table 4.3). Therefore, the limb tested did not influence the children's foot structure. However, when data were pooled across test limb significant differences between the obese and non-obese subjects were found for 17 of the 26 foot structure variables (see Table 4.3).

Table 4.2 Foot anthropometry data obtained for the right and left feet of the non-obese (n = 10) and obese (n = 10) subjects.

	Non-obese				Obese			
	Right		Left		Right		Left	
Variable (mm)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Calf Height	259	30	259	30	290	53	279	30
Ankle Height	91	12	89	12	92	12	92	9
Medial Malleolus Height	64	5	63	5	65	5	67	6
Lateral Malleolus Height	59	7	58	7	63	8	65	10
Bimalleolar Breadth	57	6	56	5	60	5	61	6
Heel Breadth	48	3	49	3	54	5	54	5
BOF‡ Diagonal Breadth	74	6	74	7	83	8	83	8
Calf Circumference	270	29	269	29	333	30	334	32
Ankle Circumference	193	19	189	18	219	20	222	25
Heel-Ankle Circumference	274	25	276	27	296	50	304	25
Instep Circumference	208	16	207	17	228	18	231	19
BOF Circumference	201	16	201	16	200	66	220	17
Dorsal Arch Height	67	9	69	11	75	11	75	9
Plantar Arch Height	18	7	18	7	18	12	18	8
Ball of Foot Height	30	4	28	4	34	5	34	6
Great Toe Height	23	2	23	3	28	4	27	2
Maximum Toe Height	21	1	21	2	24	2	24	2
Outside BOF Height	18	2	18	2	21	3	20	2
Ankle Length	83	14	83	13	91	10	88	9
Instep Length	108	14	107	13	113	13	110	12
Ball of Foot Length	147	16	152	17	160	19	161	12
Foot Length	214	20	216	19	224	21	224	18
BOF Horizontal Breadth	77	5	76	6	87	7	84	9
Outside BOF Length	131	10	131	12	139	12	142	14
5th Toe Length	173	15	171	16	181	16	182	16
1st - 3rd Toe Breadth	56	7	55	6	63	6	62	6

‡ BOF = Ball of foot

Table 4.3 F-ratios and p-values derived for each source of variance for the foot anthropometry data obtained for the non-obese (n = 10) and obese (n = 10) subjects.

Variable	Limb effect $F_{(1, 36)}$	Limb effect p-value	Obesity effect $F_{(1, 36)}$	Obesity effect p-value	Limb x Obesity $F_{(1, 36)}$	Limb x Obesity p-value
Calf Height	0.223	0.639	4.775	0.035*	0.235	0.631
Ankle Height	0.111	0.741	0.173	0.713	0.003	0.956
Medial Malleolus Height	0.041	0.841	1.755	0.194	1.007	0.322
Lateral Malleolus Height	0.023	0.881	3.110	0.086	0.310	0.581
Bimalleolar Breadth	0.059	0.809	3.876	0.057	0.090	0.766
Heel Breadth	0.010	0.919	14.608	<0.001*	0.166	0.686
BOF‡ Diagonal Breadth	0.043	0.836	16.161	<0.001*	0.027	0.871
Calf Circumference	0.002	0.990	44.744	<0.001*	0.011	0.918
Ankle Circumference	0.003	0.959	19.597	<0.001*	0.272	0.605
Heel-Ankle Circumference	0.183	0.671	5.474	0.025*	0.078	0.782
Instep Circumference	0.443	0.835	15.042	<0.001*	0.167	0.685
BOF Circumference	0.001	0.971	11.852	0.001*	0.008	0.931
Dorsal Arch Height	0.189	0.667	4.219	0.047*	0.039	0.844
Plantar Arch Height	0.041	0.841	0.006	0.940	0.036	0.851
Ball of Foot Height	0.441	0.511	11.797	0.002*	0.251	0.619
Great Toe Height	0.513	0.478	17.114	<0.001*	0.791	0.380
Maximum Toe Height	0.064	0.802	21.234	<0.001*	0.673	0.417
Outside BOF Height	0.608	0.441	14.039	<0.001*	0.191	0.665
Ankle Length	0.219	0.643	2.723	0.108	0.273	0.604
Instep Length	0.361	0.552	0.878	0.355	0.113	0.739
Ball of Foot Length	0.205	0.653	4.447	0.042*	0.224	0.639
Foot Length	0.003	0.955	1.985	0.167	0.042	0.840
BOF Horizontal Breadth	0.763	0.388	14.211	<0.001*	0.171	0.682
Outside BOF Length	0.067	0.797	5.458	0.025*	0.114	0.738
5th Toe Length	0.017	0.898	3.291	0.078	0.052	0.821
1st - 3rd Toe Breadth	0.277	0.602	9.989	0.003*	0.003	0.958

* Denotes significant difference at $p \leq 0.05$.
‡ BOF = Ball of foot

Significant main effects of obesity were found for 17 of the foot anthropometry variables when the data were pooled across test limbs. *Post hoc* tests confirmed that the obese subjects had significantly greater mean calf height (285 ± 42 mm; q = 3.090), heel breadth (54 ± 5 mm; q = 5.405), and ball of foot diagonal breadth (83 ± 8 mm; q =

5.685) compared to the non-obese subjects (259 ± 29 mm; 49 ± 3 mm; 74 ± 6 mm, respectively). Furthermore, the obese subjects had significantly greater mean circumference measurements for the calf (334 ± 30 mm; q = 9.460), ankle (221 ± 22 mm; q = 6.261), heel-ankle (300 ± 38 mm; q = 3.309), instep (230 ± 18 mm; q = 5.485) and ball of foot (220 ± 17 mm; q = 4.689) compared to their non-obese counterparts (270 ± 28 mm; 192 ± 18 mm; 276 ± 25 mm; 208 ± 16 mm; 201 ± 16 mm, respectively). The obese subjects also displayed significantly greater mean dorsal arch height (75 ± 10 mm; q = 2.904), ball of foot height (34 ± 5 mm; q = 4.857), great toe height (27 ± 3 mm; q = 5.850), maximum toe height (24 ± 2 mm; q = 6.517), outside ball of foot height (21 ± 2 mm; q = 5.299), ball of foot length (161 ± 15 mm; q = 2.982), ball of foot horizontal breadth (86 ± 8 mm; q = 5.331), outside ball of foot length (140 ± 13 mm; q = 3.304) and 1st to 3rd toe breadth (62 ± 5 mm; q = 4.470) compared to the non-obese subjects (69 ± 10 mm; 29 ± 4 mm; 23 ± 3 mm; 21 ± 2 mm; 18 ± 2 mm; 150 ± 16 mm; 77 ± 5 mm; 131 ± 15 mm; 56 ± 6, respectively).

From these results, it is evident that obese children have significantly broader, higher, and thicker structural features in their feet compared to their non-obese counterparts. The findings from this study are extremely important as they clearly show that obese children have foot dimensions and foot shape that differ markedly compared to non-obese children. In order to achieve correct shoe fit, shoe shape should be matched to foot shape (Wunderlich & Cavanagh, 1999). Anecdotal evidence suggests that obese children often have difficulties obtaining correctly fitting shoes. However, if shoes do not fit correctly, there are potentially many negative consequences for both structure and function of the developing foot. In addition, incorrect fitting shoes may cause discomfort for the obese child, potentially decreasing their motivation to participate in activities and, in turn, perpetuating the cycle of obesity. Based on the present findings it is recommended that a shoe last should be developed to cater specifically for the unique structural characteristics of the feet of the obese children. This would provide the foundation upon which to develop shoes that adequately fit the feet of these children. At present, shoe lasts for children's shoes are constructed as smaller versions of the adult female shoe last which itself is a cut-down version of the adult male shoe last (Doherty, personal communications, 2001). Therefore, it is not surprising that obese children have difficulties finding correctly fitting shoes if the shoes available are merely cut-down versions of an adult male shoe. Development of shoe lasts for obese children require specific information pertaining to their unique foot structural characteristics as highlighted by the results of the present study.

4.2 Footprint Angle, Chippaux-Smirak Index, and Arch Index Data

Descriptive statistics pertaining to the FA, CSI and AI values for the non-obese and obese subjects are presented in Table 4.4. The FA, CSI and AI values obtained for the non-obese subjects are comparable to values reported previously in the literature for other groups of non-obese children of similar age (Forriol & Pascual, 1990; Riddiford-Harland *et al.*, 2000; Dowling *et al.*, 2001). Furthermore, when the data were pooled across subject groups, there was no main effect of limb on FA, CSI or AI (see Table 4.5), indicating that the values were not limb dependent. Differences between a subject's right and left foot were not expected as no child presented for testing with unilateral foot pathology.

Despite no limb effect, there was a significant main effect of obesity on the CSI and AI data but the not FA data (see Table 4.5). That is, *post hoc* tests revealed significantly higher mean CSI (33.68 ± 15.6%; q = 3.768) and AI (0.22 ± 0.07; q = 3.472) values for the obese subjects compared to the non-obese subjects (19.53 ± 17.23% and 0.163 ± 0.079, respectively). Although the obese subjects did display lower FA values on average (33 ± 12°) compared to their non-obese counterparts (39 ± 8°), this difference was not significantly different (p = 0.09).

Table 4.4 Footprint Angle, Chippaux-Smirak Index and Arch Index data obtained for the right and left feet of the non-obese (n = 10) and obese (n = 10) subjects.

	Non-obese				Obese			
	Right		Left		Right		Left	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Footprint Angle (°)	37	9	42	6	34	12	33	12
Chippaux-Smirak Index (%)	20.27	18.01	18.79	17.35	35.70	15.65	31.66	16.06
Arch Index	0.16	0.08	0.16	0.08	0.22	0.08	0.23	0.06

Table 4.5 F-ratios and *p*-values derived for each source of variance for the Footprint Angle, Chippaux-Smirak Index and Arch Index data obtained for the non-obese (n = 10) and obese (n = 10) subjects.

Variable	Limb effect $F_{(1, 36)}$	*p*-value	Obesity effect $F_{(1, 36)}$	*p*-value	Limb x Obesity $F_{(1, 36)}$	*p*-value
Footprint Angle (°)	0.453	0.505	3.041	0.090	0.734	0.397
Chippaux Smirak Index (%)	0.270	0.606	7.098	0.011*	0.058	0.811
Arch Index	0.043	0.836	6.029	0.019*	0.058	0.811

* Denotes significant difference at $p \leq 0.05$.

The significantly higher CSI and AI values displayed by the obese children compared to their non-obese counterparts, indicated that these children had a lowered arch and a flat arch foot when analysed according to the CSI classifications and AI categories (see Table 3.4 and 3.5, respectively). These structural characteristics of the foot displayed by the obese children are consistent with the findings of Riddiford-Harland *et al.* (2000) and Dowling *et al.* (2001) who reported that obese prepubescent children displayed a broader, flatter plantar surface area of the foot compared to the non-obese children when assessed using similar analytical techniques (see Section 2.3). Furthermore, combined with the thicker, broader, higher foot structure results noted in Section 4.2, the CSI and AI results support the notion that obese children have a different foot shape and foot structure compared to their non-obese counterparts. Therefore, it is again recommended that a shoe last designed specifically for the unique characteristics of obese children be developed (see Section 4.1).

4.3 Foot Sensation

Means and standard deviations for the pressure and vibration values obtained for the obese and non-obese subjects are included in Table 4.6. No data could be found for children against which to compare these values obtained in the present study. The mean of 1 obtained for the vibration stimuli is equivalent to the rank given to represent a positive response to the vibration stimuli. The mean of 3 for the pressure stimuli is again equivalent to the rank given to represent a positive response to the 5.07 monofilament, which is the monofilament used to determine any decrement in foot sensations. Therefore, both groups of children were able to detect the vibration and pressure stimuli.

Table 4.6 Pressure and vibration data obtained for the non-obese (n = 10) and obese (n = 10) subjects.

Variable	Non-obese Mean	SD	Obese Mean	SD	*t*-value	*p*-value
Pressure (ranked data)	3	0	3	0	1	0.969
Vibration (ranked data)	1	0	1	0	1	0.969

Furthermore, no significant differences between the obese and non-obese children were found for either the vibration or the pressure data. These findings suggest that obese children at this young age, display no sign of decrementing foot sensation. It is also postulated that early signs of diabetic neuropathy are not evident in young obese children, although there is an increased risk for obese adults to develop Type II diabetes (see Section 2.0). However, the present findings should be interpreted with some degree of caution as the clinical tools used in this study, although internationally accredited, do have limitations with respect to their sensitivity. Therefore, it is recommended that, although there appears to be no effect of childhood obesity on foot vibration and pressure sensation in this study, further research in this area is warranted.

4.4 Joint Range of Motion

In Table 4.7, means and standard deviations for the plantar flexion and dorsiflexion values obtained for the obese and non-obese subjects are presented. The present data differ substantially from plantar flexion (59.6 ± 4.7°) and dorsiflexion (13.8 ± 4.4°) range of motion results reported for 6 to 12 year old children by Boone & Azen (1979). Even the total joint range of motion reported by Boone & Azen (1979), 73.4°, was considerably greater than the total joint range of motion obtained in this study, 57.75°. However, this between-study difference is attributed to the fact that plantar flexion and dorsiflexion range of motion data were assessed passively in the present study whereas Boone & Azen (1979) assessed these characteristics actively. The present findings were comparable to the passive range of motion values reported for adults in Norkin &

Levangie (1992) and Kapandji (1987), where the normal adult plantar flexion range of motion measured from neutral was 30 to 50° and the dorsiflexion range of motion was 20 to 30°.

Table 4.7 Plantar flexion and dorsiflexion data obtained for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variable (°)	Non-obese				Obese			
	Left		Right		Left		Right	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Plantar flexion	34	5	25	6	27	7	33	13
Dorsiflexion	33	5	25	8	37	7	23	9

A significant main effect of limb on dorsiflexion range of motion was found when the obesity data were pooled across subject groups (see Table 4.8). That is, the children displayed a greater mean dorsiflexion range of motion for their left limb (31 ± 10°; q = 6.497) compared to their right limb (28 ± 9°). However, this difference is only 3°. Considering inherent limitations with the accuracy of range of motion measurements, particularly those measured manually, such a small difference would be not be clinically significant.

Table 4.8 F-ratios and p-values derived for each source of variance for the plantar flexion and dorsiflexion data obtained for the non-obese (n = 10) and obese (n = 10) subjects.

Variable (°)	Limb		Obesity		Limb x Obesity	
	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value
Plantar flexion	0.715	0.403	0.072	0.789	7.877	0.008*
Dorsiflexion	21.105	<0.001*	0.455	0.504	1.494	0.230

* Denotes significant difference at $p \leq 0.05$.

Although there was no effect of obesity on the range of motion data, there were significant interactions between limb and obesity for the plantar flexion range of motion results. That is, the obese children displayed greater mean plantar flexion range of motion (33 ± 13°; q = 3.076) compared to the non-obese subjects (25 ± 6°) for their left

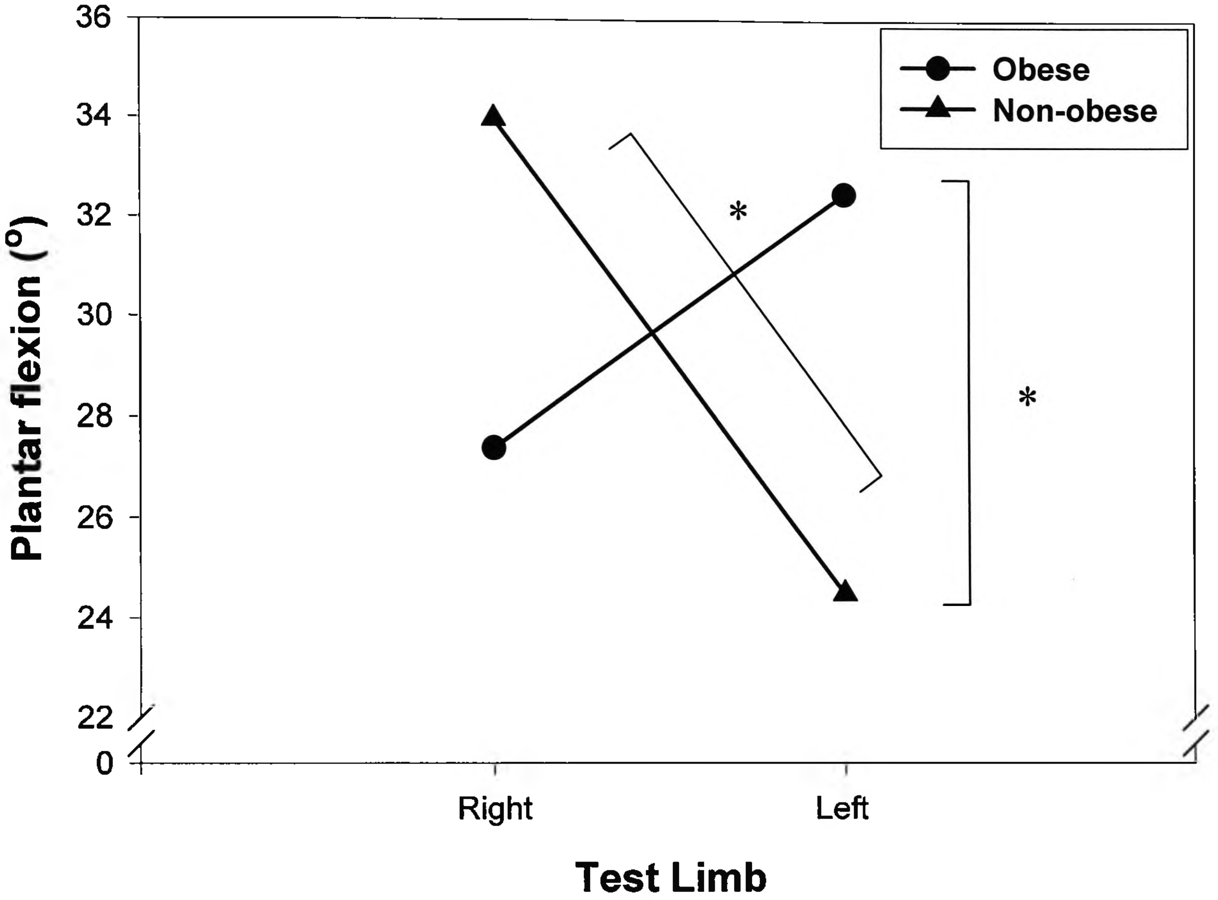


Figure 4.1 Test limb x subject group interactions for the plantar flexion data.
* Denotes significant interaction.

limb. However, the reverse was noted for the right limb whereby the non-obese subjects displayed greater mean plantar flexion range of motion (34 ± 5°; q = 3.652) compared to the left limb of the non-obese subjects (25 ± 6°; see Figure 4.1). The reason for this significant interaction between limb and obesity for the plantar flexion range of motion results is not apparent and the implications of this finding are not clear. It is possible that the data may reflect effects of limb dominance that may have, in turn, influenced the range of motion data. However, this notion is purely speculative as limb dominance was not assessed in the present study. Therefore, it is recommended that the effect of obesity on joint range of motion for the talocrural joint be re-examined.

4.5 Rearfoot Alignment and Motion

4.5.1 Effect of Limb, Obesity and Stance on Rearfoot Alignment

Descriptive statistics for the values of rearfoot angle and Achilles tendon angle obtained for the right and left feet of the obese and non-obese subjects when they were standing in the three positions (see Section 3.1.7) are included in Table 4.9. Sobel *et al.* (1999) reported comparable rearfoot angles of 4°[∀] valgus for children of normal body mass, although the effects of stance was not considered. No study could be found against which to compare the Achilles tendon angle values of children standing in any of the three different test positions used.

A significant main effect of stance was found for the rearfoot angle values when the data were pooled across both test limb and subject groups (see Table 4.10). That is, the children displayed a significantly greater mean rearfoot angle when standing with their heels placed 20 cm apart (96 ± 4°; q = 11.657) compared to standing with their heels together (86 ± 6°). When standing with heels 20 cm apart (96 ± 4°; q = 3.374) the mean rearfoot angle displayed was also significantly greater compared to when the children were standing with their feet comfortably apart (93 ± 5°). Additionally, when the children were standing comfortably, the mean rearfoot angle (93 ± 5°; q = 8.283) was significantly greater compared to when they were standing with heels together (86 ± 6°). These findings suggest that placement of the heels and the distance the feet are apart are

[∀] Four degrees equates to 86° from the horizontal when converted to the same measurement convention as used in this study.

important factors to consider when determining rearfoot angle, a factor overlooked by most current published studies. Placing the heels together created a narrower base of support and, in turn, greater inward angulation of the femur. To compensate the children tended to display calcaneal valgus. In contrast, when allowed to adopt a more natural stance (feet comfortably apart), the children's lower limb segments, including their rearfoot, were more vertically aligned. Creating a wider base of support by forcing the feet further apart, resulted in calcaneal varus as the children compensated for the change in lower limb segmental alignment.

Table 4.9 Rearfoot angle and Achilles tendon angle data obtained for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects during stance.

Variable	**Non-obese**				**Obese**			
	Left		**Right**		**Left**		**Right**	
Stance (°)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
RF[§] Together	86	6	87	5	87	7	84	6
RF 20 cm Apart	96	5	96	6	95	3	96	3
RF Comfortable	93	6	91	5	93	5	94	5
AT[£] Together	181	6	179	6	178	7	182	6
AT 20 cm Apart	180	7	175	7	183	4	177	4
AT Comfortable	180	7	178	6	182	3	180	6

§ RF = rearfoot angle
£ AT = Achilles tendon angle

Sobel *et al.* (1999) and Riddiford-Harland *et al.* (2000) have previously reported that body mass does not influence rearfoot angle data in children (see Section 2.4). Results of the present study further support this notion in that there was no significant effect of obesity on rearfoot angle. Therefore, long-term excessive weight bearing does not appear to influence alignment of the rearfoot when standing statically.

A significant main effect of limb on Achilles tendon angle was found when stance and obesity data were pooled (see Table 4.10). That is, the children displayed a greater mean Achilles tendon angle for their left limb (181 ± 6°; q = 3.178) compared to their right limb (179 ± 6°). This greater Achilles tendon angle may be related to the previously reported limb effect of dorsiflexion range of motion (see Section 4.5) whereby the children displayed greater joint dorsiflexion range of motion for their left limb compared to the right limb. However, as these variables represent different planes in which motion occurs, the relationship is only speculative. Conversely, it is possible that the children may not have been standing with an equal weight bearing distribution or the results may have been influenced by the position of their feet relative to the camera (Areblad *et al.* 1990; see Section 4.7). However, as the between-limb difference was only 2°, the clinical significance would be negligible. Despite the effect of limb there was no significant main effect of obesity on Achilles tendon angle when test limb and stance data were pooled. Therefore, these findings again support the notion that long-term excessive weight bearing does not influence static lower limb alignment.

Table 4.10 F-ratios and *p*-values derived for each source of variance for rearfoot angle and Achilles tendon angle data obtained in the stance positions for the non-obese (n = 10) and obese (n = 10) subjects.

Variable (°)	Obesity $F_{(1,119)}$	Obesity *p*-value	Limb $F_{(1,119)}$	Limb *p*-value	Stance $F_{(1,119)}$	Stance *p*-value	Obesity x Limb $F_{(1,119)}$	Obesity x Limb *p*-value
RF	0.033	0.856	0.329	0.568	35.978	<0.001*	0.008	0.928
AT	1.711	0.194	5.05	0.027*	0.607	0.547	0.327	0.569

Variable (°)	Obesity x Stance $F_{(1,119)}$	Obesity x Stance *p*-value	Limb x Stance $F_{(1,119)}$	Limb x Stance *p*-value	Obesity x Limb x Stance $F_{(1,119)}$	Obesity x Limb x Stance *p*-value
RF	0.39	0.678	0.074	0.929	0.844	0.433
AT	0.208	0.813	2.13	0.124	1.084	0.342

* Denotes significant difference at $p \leq 0.05$.

4.5.2 Effect of Limb and Obesity on Rearfoot Motion

Means and standard deviations for the dynamic rearfoot angle and Achilles tendon angle data obtained for the right and left feet of the obese and non-obese subjects at initial contact and midstance during walking are included in Table 4.11. No study could be found against which to compare these dynamic values of rearfoot angle and Achilles tendon angle for normal mass children during gait. Furthermore, barefoot gait studies examining adults have not used the same angles to characterise rearfoot motion at the same times during the stance phase as were used in this study (see Section 3.2.4). However, studies conducted by Nigg (1986) pertaining to varying shoe conditions have indicated that adults display similar rearfoot and Achilles tendon angle values at initial contact when walking compared to data found for the children in the present study. Observation of the change in Achilles tendon and rearfoot angle between initial contact and midstance indicates that, on average, the children displayed minimal motion (1° to 3°) of their rearfoot and distal tibia during this phase of the gait cycle. However, the standard deviations calculated for these variables are high (see Table 4.11), indicating a wide variation on these parameters between the subjects.

Table 4.11 Rearfoot angle and Achilles tendon data obtained for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects during gait.

Variable	**Non-obese**				**Obese**			
	Left		**Right**		**Left**		**Right**	
(°)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
IC† Achilles	183	5	185	6	177	7	183	5
IC Rearfoot	91	4	87	6	95	8	89	5
MS‡ Achilles	179	4	183	6	177	4	178	11
MS Rearfoot	91	4	86	6	92	4	90	7
Change in Achilles	1	5	1	6	<1	7	3	9
Change in Rearfoot	1	3	1	5	2	6	2	7

† IC = Initial contact
‡ MS = Midstance

When the data were pooled across subject groups, a significant main effect of limb was found for the Achilles tendon angle at initial contact (see Table 4.12). That is, the children displayed a greater mean Achilles tendon angle at initial contact for their right limb (184 ± 5°; q = 2.968) compared to their left limb (mean = 180 ± 7°). In addition, the children displayed a greater mean rearfoot angle at initial contact for their left limb (92 ± 7°; q = 3.193) compared to their right limb (88 ± 5°). This pattern is also evident at midstance where the children's left limb (91 ± 4°; q = 2.999) also displayed a greater mean rearfoot angle compared to the right limb (88 ± 6°). However, there was no significant main effect of obesity on rearfoot motion when the data were pooled across limbs and no significant obesity x limb interactions. As for the static rearfoot alignment parameters, there are errors inherent in attempting to characterise rearfoot motion dynamically, including the sensitivity of two-dimensional assessment techniques to alignment of the foot relative to the video camera (Areblad *et al.*, 1990). As the between-limb differences found in the present study were again relatively small, it is recommended that the effects of limb and obesity on rearfoot motion be re-examined but using three-dimensional analysis techniques.

Table 4.12 F-ratios and p-values derived for each source of variance for the rearfoot angle and Achilles tendon angle data obtained for the non-obese (n = 10) and obese (n = 10) subjects during gait.

Variable	Limb		Obesity		Obesity x Limb	
	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value
IC† Achilles	4.406	0.043*	3.977	0.054	0.954	0.335
IC Rearfoot	5.096	0.030*	3.034	0.090	0.931	0.341
MS‡ Achilles	0.932	0.341	2.820	0.102	0.471	0.497
MS Rearfoot	4.496	0.041*	1.202	0.280	0.724	0.401
Change in Achilles	0.560	0.459	0.021	0.885	0.634	0.431
Change in Rearfoot	0.312	0.580	0.026	0.882	3.357	0.075

* Denotes significant difference at $p \leq 0.05$.
† IC = Initial contact
‡ MS = Midstance

4.6 Static Plantar Pressure

Means and standard deviations for the static plantar pressure values obtained for the right and left feet of the obese and non-obese subjects are included in Table 4.13. A previous study by Dowling *et al.* (2001) examined static peak pressure, peak area and peak force data for prepubescent children reporting slightly lower force and pressure values (see Section 2.5) compared to the present values, although the area data were similar. This between-study difference may be due to the different pressure measurement systems used in the two studies whereby the AT-4 platform has an increased number of sensors per unit of area and an increased sampling frequency compared to the mini-emed pressure platform system used by Dowling *et al.* (2001). Furthermore, children aged from 6 to 12 years were included as subjects in the present study compared to children who were only between 7 to 10 years of age in the study of Dowling *et al.* (2001). The older children in the present study were on average heavier, increasing the forces generated on the plantar surface of their feet.

Table 4.13 Static peak force, area and pressure data for the right and left feet of the non-obese (n =10) and obese (n =10) subjects.

	Non-obese				Obese			
	Right		Left		Right		Left	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
PF[#] (N)	348.37	125.37	440.16	142.09	688.68	228.75	698.08	247.40
PA (cm^2)	54.16	12.04	60.06	12.96	87.00	21.55	86.25	21.24
PP ($N{\cdot}cm^{-2}$)	26.20	8.49	34.08	14.11	37.03	9.36	45.50	22.37

\# PF = Peak force, PA = Peak area, PP = Peak pressure.

Two-way ANOVA results for the effect of limb found no differences between the left and right feet of the subjects for peak force, peak area and peak pressure when the data were pooled across subject groups (see Table 4.14). However, statistical main effects of obesity were found on peak pressure, peak area and peak force when the data were pooled across test limb data (see Table 4.14). *Post hoc* tests confirmed that the obese subjects displayed significantly higher mean static peak forces (690.87 ± 231.0 N; q = 6.921) compared to the non-obese subjects (394.27 ± 138.7 N). Dowling *et al.* (2001) reported similar findings whereby obese prepubescent children displayed significantly higher mean peak forces (377.93 ± 105.94 N; q = 11.322) than the non-obese children (249.92 ± 53.76 N). As force is equal to the product of mass and acceleration, this increase in the static peak force displayed by the obese children, with their larger body mass, was expected. Similar increases in static peak force values have been reported for adults relative to their leaner counterparts by Hennig *et al.* (1998). Based on these results and the previous findings of Dowling *et al.* (2001) it was confirmed that increased body mass, associated with childhood obesity, resulted in greater peak force to be exerted on the plantar surface of the feet during standing.

Table 4.14 F-ratios and *p*-values derived for each source of variance for the peak force, peak area and peak pressure data obtained for the non-obese (n = 10) and obese (n = 10) subjects.

Variable	Limb effect		Obesity effect		Limb x Obesity	
	$F_{(1, 36)}$	*p*-value	$F_{(1, 36)}$	*p*-value	$F_{(1, 36)}$	*p*-value
PF# (N)	0.685	0.413	23.948	<0.001*	0.454	0.505
PA (cm²)	0.216	0.645	28.368	<0.001*	0.360	0.552
PP ($N \cdot cm^{-2}$)	3.112	0.086	5.763	0.022*	0.004	0.949

* Denotes significant difference at $p \leq 0.05$.
\# PF = Peak force, PA = Peak area, PP = Peak pressure.

In Table 4.14, a significant main effect of obesity was also found for peak area data when the test limb data were pooled. *Post hoc* analysis revealed that the mean peak area data was significantly higher in the obese group (86.46 ± 20.7 cm^2; q = 7.532) compared to the non-obese group (57.11 ± 12.5 cm^2). That is, the obese children displayed a significantly greater area of the plantar surface of their feet in contact with the ground, compared to their non-obese counterparts. This greater contact area is consistent with the previous finding revealed by the other footprint parameters of FA, AI and CSI, which indicated that obese subjects had lowered arches and flatter feet than the non-obese children (see Section 4.2.2). Welton's (1992) association of plump and obese individuals as having broader footprints is also consistent with this finding of a higher area of the foot in contact with the pressure platform for the obese group in the present study.

A main effect of obesity on peak pressure data was also found in the present study when the test limb data were pooled. That is, *post hoc* tests confirmed that the obese subjects experienced higher mean static peak pressures (41.80 ± 17.7 $N \cdot cm^{-2}$; q = 3.395) compared to their non-obese counterparts (30.14 ± 12.0 $N \cdot cm^{-2}$). This significant main effect of obesity on peak pressure is contrary to previous findings by Dowling *et al.* (2001) who reported no significant difference in the static peak pressure recorded for the obese subjects (16.5 ± 4.8 $N \cdot cm^{-2}$) compared to the non-obese subjects (15.1 ± 5.0 $N \cdot cm^{-2}$). The increased forces generated by the obese children in both studies were experienced over a larger surface area of the foot. However, although the children in the study by Dowling *et al.* (2001) were able to effectively dissipate these higher forces over a large enough area to minimise any pressure increase, the obese children in the current study did not successfully achieve this. That is, the increase in foot contact area was not great enough to effectively dissipate the higher static forces, thus increasing the pressures generated on the plantar surfaces of their feet. As the pressure measurement platform used in the present study was more sensitive than the system used by Dowling *et al.* (2001), it is postulated that the present results where obese children generated higher static plantar pressures during standing relative to their non-obese counterparts is the more valid result. This has serious implications for the obese child as this higher plantar pressure during static weight bearing may potentially cause discomfort to their feet and may increase the risk of developing other foot pathologies (see Section 2.5). Whether this increased plantar pressure displayed by the obese children extends to walking is presented below.

4.7 Dynamic Plantar Pressure

Descriptive statistics pertaining to total foot, rearfoot and forefoot force, area and pressure values obtained for the right and left feet of the obese and non-obese children during walking are presented in Table 4.15. The peak force, area and pressure data in this table are comparable to previous data reported for normal children by David *et al.* (1999) and Dowling *et al.* (2001; see Table 2.4). However, data recorded in this study is higher than results reported by Hennig *et al.* (1994) for children aged 6 to 10 years of age. These between-study differences may again be explained by variations in the number of sensors in the pressure platforms used, the collection frequency and the age range of the subjects tested.

4.7.1 <u>Effects of Limb and Obesity on Total Foot Peak Force, Area and Pressure</u>

There was no main effect of limb on total foot peak force, area or pressure when the data were pooled across subject groups. However, significant main effects of obesity were found for peak force and peak area (see Table 4.16). That is, the peak mean forces generated by the obese subjects across their total foot when walking (1017.84 ± 256.0 N; q = 7.676) were significantly higher than those generated by the non-obese subjects (647.83 ± 150.5 N). In support of this finding, Smahel (1980), Hennig *et al.* (1994) and

Dowling *et al.* (2001) all previously reported increases in dynamic plantar pressure forces across the foot as body mass increased. Similar to the static results, this finding was anticipated, as force is equivalent to mass x acceleration, whereby the subjects were encouraged to walk at a consistent pace as set by an accompanying walker.

Table 4.15 Dynamic peak, rearfoot and forefoot force, area and pressure for the non-obese (n = 10) and obese (n = 10) subjects for both left and right feet.

Variable		**Non-obese**				**Obese**			
		Right		**Left**		**Right**		**Left**	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Total foot	**PP[¥] ($N \cdot cm^{-2}$)**	82.28	23.9	76.25	20.7	89.66	29.3	85.73	21.7
	PA (cm^2)	64.78	8.5	65.43	9.2	90.44	17.9	89.96	19.5
	PF (N)	652.29	142.2	643.37	166.0	1006.75	259.6	1028.93	265.9
Rearfoot	**PP ($N \cdot cm^{-2}$)**	65.80	24.4	58.57	11.5	65.44	19.1	70.19	21.4
	PA (cm^2)	26.15	6.3	25.70	5.8	40.01	10.1	38.57	11.1
	PF (N)	459.64	134.0	425.68	101.2	694.63	197.0	697.35	203.5
Forefoot	**PP ($N \cdot cm^{-2}$)**	75.08	28.5	71.03	23.3	86.07	31.6	76.26	21.0
	PA (cm^2)	44.62	4.8	44.71	6.1	57.93	10.1	58.54	10.2
	PF (N)	603.16	140.2	595.91	151.8	964.35	274.2	967.58	254.6

[¥]PP = Peak pressure, PA = Peak area, PF = Peak force.

A significant main effect of obesity, as seen in Table 4.16, was found for total foot peak area, whereby obese subjects displayed significantly higher mean peak areas of contact with the AT-4® system when walking (90.20 ± 18.2 cm^2; q = 7.666) compared to the non-obese subjects (65.11 ± 8.6 cm^2). However, despite significant main effects for both peak force and peak area, there was no main effect of obesity on dynamic peak pressure data for the whole foot when the data were pooled across test limbs. This is consistent with the dynamic data reported by Dowling *et al.* (2001; see Table 2.4), where the obese subjects generated greater peak forces than their non-obese counterparts, although these forces were experienced over a greater contact area and therefore resulted in minor or no changes in total foot peak pressures. Based on these results it is postulated that the increased area of foot contact during walking caused by the long-term bearing of additional mass, as in obesity, may be due to flattening of a structure such as the plantar plate, which is not as compromised during static standing. However, the actual mechanism of the increased area of contact in the obese children's total foot during walking is speculative and warrants further investigation.

Table 4.16 F-ratios and p-values derived for each source of variance for the peak force, area, pressure, rearfoot force, area, pressure and forefoot force, area and pressure data with limb condition and the obesity factor.

Variable		**Limb effect** $F_{(1, 36)}$	p**-value**	**Obesity effect** $F_{(1, 36)}$	p**-value**	**Limb x Obesity** $F_{(1, 36)}$	p**-value**
Total foot	**PP**[¥] **(N·cm**$^{-2}$**)**	0.425	0.518	1.219	0.277	0.019	0.891
	PA (cm^{2}**)**	<0.001	0.986	29.385	<0.001*	0.015	0.903
	PF (N)	0.010	0.923	29.460	<0.001*	0.052	0.821
Rearfoot	**PP (N·cm**$^{-2}$**)**	0.040	0.843	0.817	0.372	0.926	0.342
	PA (cm^{2}**)**	0.120	0.731	24.053	<0.001*	0.034	0.856
	PF (N)	0.090	0.766	23.680	<0.001*	0.124	0.727
Forefoot	**PP (N·cm**$^{-2}$**)**	0.686	0.413	0.941	0.339	0.119	0.733
	PA (cm^{2}**)**	0.018	0.893	27.833	<0.001*	0.010	0.920
	PF (N)	0.001	0.976	29.393	<0.001*	0.006	0.939

* Denotes significant difference at $p \leq 0.05$.
¥ PP = Peak pressure, PA = Peak area, PF = Peak force.

4.7.2 <u>Effects of Limb and Obesity on Rearfoot Force, Area and Pressure</u>

Descriptive statistics pertaining to rearfoot force, area and pressure obtained for the obese and non-obese subjects for their left and right feet are displayed in Table 4.15. These values are comparable to data previously presented for children by Dowling *et al.* (2001; see Table 2.4). A significant main effect of obesity on rearfoot force was found when the test limb data were pooled (see Table 4.16). That is, as anticipated, the mean peak dynamic rearfoot force was significantly higher in the obese subjects (695.99 ± 194.9 N; q = 6.882) compared to the non-obese subjects (442.66 ± 116.9 N). In addition, a significant main effect of obesity on rearfoot area was also found (see Table 4.16). *Post hoc* analysis confirmed that obese subjects displayed a significantly higher mean rearfoot area in contact with the pressure platform during walking (39.29 ± 10.3

cm^2; q = 6.936) than non-obese subjects (25.93 ± 5.9 cm^2). Similar to data reported in Section 4.7.1 for the total foot peak dynamic values, no main effect of limb or obesity was found for the rearfoot pressure data. As the effects of obesity on the rearfoot dynamic parameters mirror those found for the total foot peak dynamic values, the rationale used to explain these findings for the total foot in Section 4.7.1 can also be used to explain variations in the rearfoot variables. Furthermore, the findings in this study are again consistent with the previous results reported by Dowling *et al.* (2001).

4.7.3 Effects of Limb and Obesity on Forefoot Force, Area and Pressure

Statistical data for the forefoot force, area, and pressure obtained for the left and right feet of the obese and non-obese subjects are displayed in Table 4.15. These values are again comparable to the values reported for children by Dowling *et al.* (2001; see Table 2.4). Although no main effects of limb were found, significant main effects of obesity were found when the data were pooled across test limb for both forefoot force and area (see Table 4.16). That is, obese subjects (965.97 ± 257.6 N; q = 7.667) again displayed significantly higher mean peak dynamic forces in the forefoot region compared to their non-obese counterparts (599.53 ± 142.3 N). In addition, the obese subjects displayed significantly higher forefoot areas of contact with the AT-4® system (58.24 ± 9.9 cm^2; q = 7.461) compared to the non-obese group (44.66 ± 5.3 cm^2).

Dowling *et al.* (2001) reported that obese children generated significantly higher mean peak forces in the forefoot region when walking compared to those generated by non-obese subjects (see Table 2.4 in Section 2.5). The authors postulated that this finding was of major concern, as obese children maybe at risk of developing foot pathologies as a consequence of this higher forefoot pressure, particularly as the forefoot is composed of small bones and has a decreased ability to dissipate forces associated with dynamic weight bearing tasks.

However, contrary to previous work by Dowling *et al.* (2001) no significant main effects of obesity were found on forefoot pressure in the present study when the test limb data were pooled (p = 0.339; see Table 4.16), although there was a non-significant increase in forefoot pressures for the obese children relative to their non-obese counterparts. David *et al.* (1999) reported higher forefoot pressure and area for the obese children although these values were not significantly different to their non-obese counterparts. As increases in these forefoot pressures might have detrimental health implications for the obese child, it is imperative that the influence of obesity on these dynamic pressures is more clearly understood. A more comprehensive analysis of these dynamic pressures via examining discrete locations on the foot via masks was therefore undertaken with the results presented below.

4.7.4 Effects of Limb and Obesity on the Masked Regions for Maximum Force

To enable a more comprehensive analysis of the effects of obesity on plantar pressure parameters generated during gait, the foot was subdivided into 10 discrete regions (masks) as were described in Section 3.2.5. Descriptive statistics pertaining to the maximum force in each mask for the right and left feet of the obese and non-obese groups are presented in Table 4.17. Although no studies could be found against which to compare the maximum force values for the masked regions for normal children, the force values generated for the total foot in this analysis are comparable to the total foot force values reported by Dowling *et al.* (2001; see Table 2.4; see Section 4.7.1 and 4.7.2).

In Table 4.18 a significant main effect of obesity* was found for the whole foot and in Masks 1 to 7 when the test limb data were pooled. That is, the obese children generated higher mean maximum forces for the whole foot, Mask 1 and 2 (lateral and medial heel), Mask 3 and 4 (the midfoot region), and Masks 5 to 7 (the metatarsal heads) compared to the non-obese children (see Figure 4.2). As discussed previously, it was expected that the obese children would generate greater forces on the plantar surface of their feet due to their increased mass (see Section 4.7.1, 4.7.2, and 4.7.3). Therefore, the greater forces that were generated in the heel, midfoot and forefoot regions were anticipated. It would appear, however, that the loads exerted on the small structures in the toe regions (Masks 8, 9 & 10) were not affected by obesity.

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* No significant main effects of limb were found for any of the masked data throughout the thesis when the data were pooled across subject groups. Furthermore, no significant subject group x test limb interactions were found for any of the masked data. Therefore, only the effects of obesity on the masked data will be discussed in the remaining sections of this chapter.

Table 4.17 Maximum force in each mask for the right and left feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables (N)	Non-obese Left Mean	SD	Non-obese Right Mean	SD	Obese Left Mean	SD	Obese Right Mean	SD
Total	645.73	144.3	655.72	141.9	1029.26	264.1	1008.10	261.0
Mask 1	229.30	41.9	239.11	78.8	392.69	95.3	370.21	110.4
Mask 2	174.05	42.7	202.12	68.7	275.11	88.2	294.11	95.7
Mask 3	6.13	6.1	5.79	5.6	24.31	24.7	23.86	19.0
Mask 4	36.67	35.1	48.49	61.3	103.76	56.8	117.66	76.7
Mask 5	152.03	74.7	170.03	81.5	229.77	83.4	212.92	74.5
Mask 6	123.11	49.4	137.39	54.9	232.20	79.0	221.02	82.5
Mask 7	203.82	64.4	201.14	77.6	355.81	130.3	364.61	114.2
Mask 8	130.54	49.0	144.71	41.8	178.73	63.0	181.58	99.7
Mask 9	21.99	13.8	19.96	5.9	27.03	11.4	29.73	17.7
Mask 10	24.86	18.9	23.16	17.1	33.99	14.2	35.54	27.9

4.7.5 Effects of Limb and Obesity on the Masked Regions for the Instant in Time during the Roll-Over-Process when Maximum Force Occurred

Means and standard deviations pertaining to the instant in time during the roll-over-process when the maximum force occurred in each mask for the right and left feet of the obese and non-obese groups are presented in Table 4.19. No study could be found against which to compare these values. However, a significant main effect of obesity on the instant in time during the roll-over-process when there was maximum force in the mask was found for Mask 6, the region representing metatarsal head 2, when the test limb data were pooled (see Table 4.20). That is, the obese children generated the maximum force in Mask 6 (q = 3.467) later during the roll-over-process compared to the non-obese children (see Figure 4.3). This finding is discussed in further detail in Section 4.7.10.

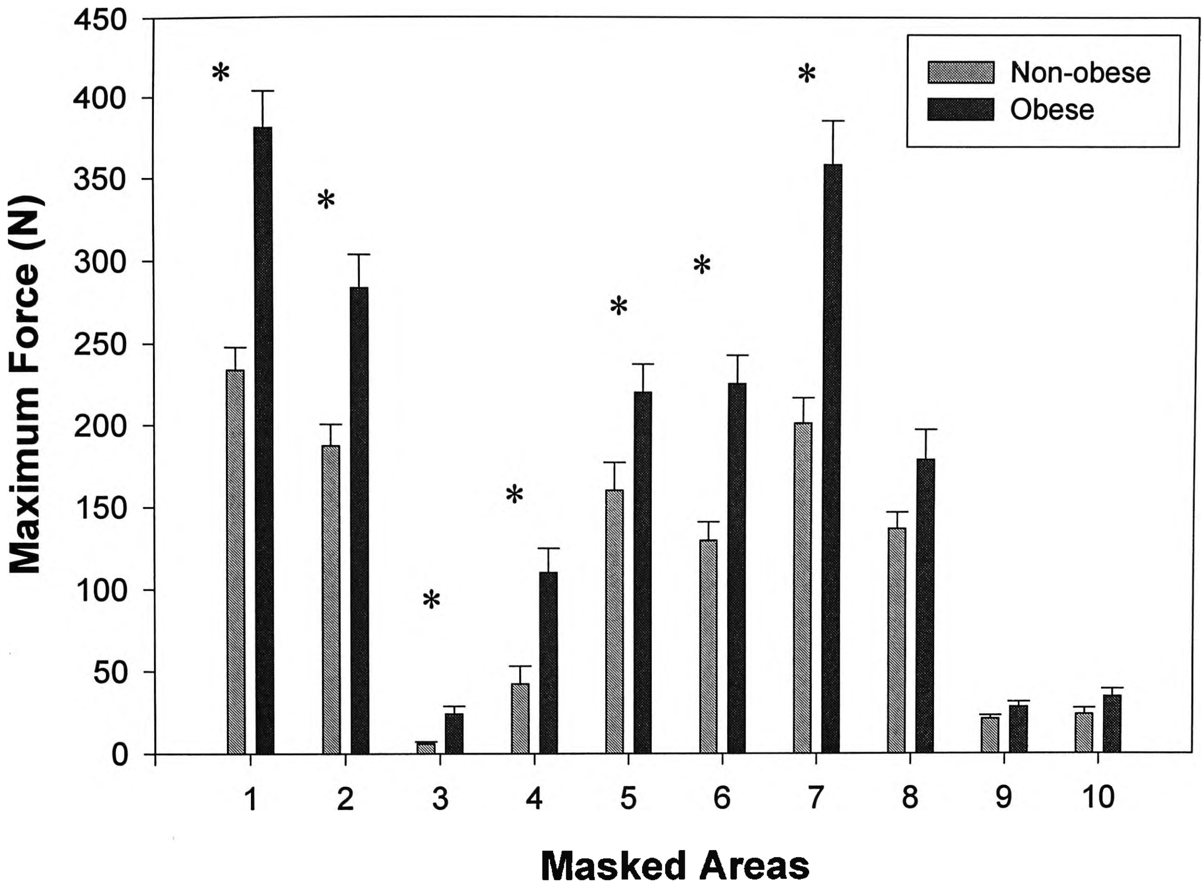

Figure 4.2 Maximum force data for each of the 10 masks (means + standard errors) for the non-obese and obese children. * Denotes significant difference. After *post hoc* analysis these masks displayed significant differences: whole foot (q = 7.783), Mask 1 (q = 7.704), Mask 2 (q = 5.634), Mask 3 (q = 5.029), Mask 4 (q = 5.133), Mask 5 (q = 3.431), Mask 6 (q = 6.336) and Mask 7 (q = 7.039).

Table 4.18 F-ratios and *p*-values derived for each source of variance for the maximum force for each of the masks with limb condition and the obesity factor.

Variable	Limb		Obesity		Limb x Obesity	
	$F_{(1, 36)}$	*p*-value	$F_{(1, 36)}$	*p*-value	$F_{(1, 36)}$	*p*-value
Total	0.007	0.934	30.290	<0.001*	0.054	0.817
Mask 1	0.055	0.816	29.679	<0.001*	0.357	0.554
Mask 2	0.943	0.338	15.872	<0.001*	0.035	0.853
Mask 3	0.006	0.938	12.644	0.001*	<0.001	0.991
Mask 4	0.469	0.498	13.175	<0.001*	0.003	0.956
Mask 5	<0.001	0.982	5.885	0.020*	0.491	0.488
Mask 6	0.005	0.943	20.07	<0.001*	0.350	0.558
Mask 7	0.009	0.924	24.772	<0.001*	0.033	0.857
Mask 8	0.160	0.691	4.006	0.053	0.071	0.791
Mask 9	0.007	0.935	3.282	0.078	0.335	0.566
Mask 10	<0.001	0.990	2.846	0.100	0.065	0.800

* Denotes significant difference at $p \leq 0.05$.

4.7.6 Effects of Limb and Obesity on the Masked Regions for Force-Time Integrals

Descriptive statistics pertaining to the force-time integrals in each mask for the right and left feet of the obese and non-obese groups are presented in Table 4.21. The highest force–time integrals generated by the children during walking in the present study were located in Mask 7, the region representing metatarsal heads 3 to 5. This finding is consistent with previous results reported by Hennig *et al.* (1994) for normal mass children in terms of the highest impulses they generated relative to the total impulse generated for the third metatarsal head during walking. However, in contrast Hennig *et al.* (1991) reported that the highest force-time integrals generated by young children were evident in the hallux region. Conversely, Borges Machado & Hennig (1999) reported that the medial heel regions displayed the highest impulses when children walked relative to the total impulse. These between-study comparisons must be interpreted carefully due to age differences in the subjects studied. For example, in the

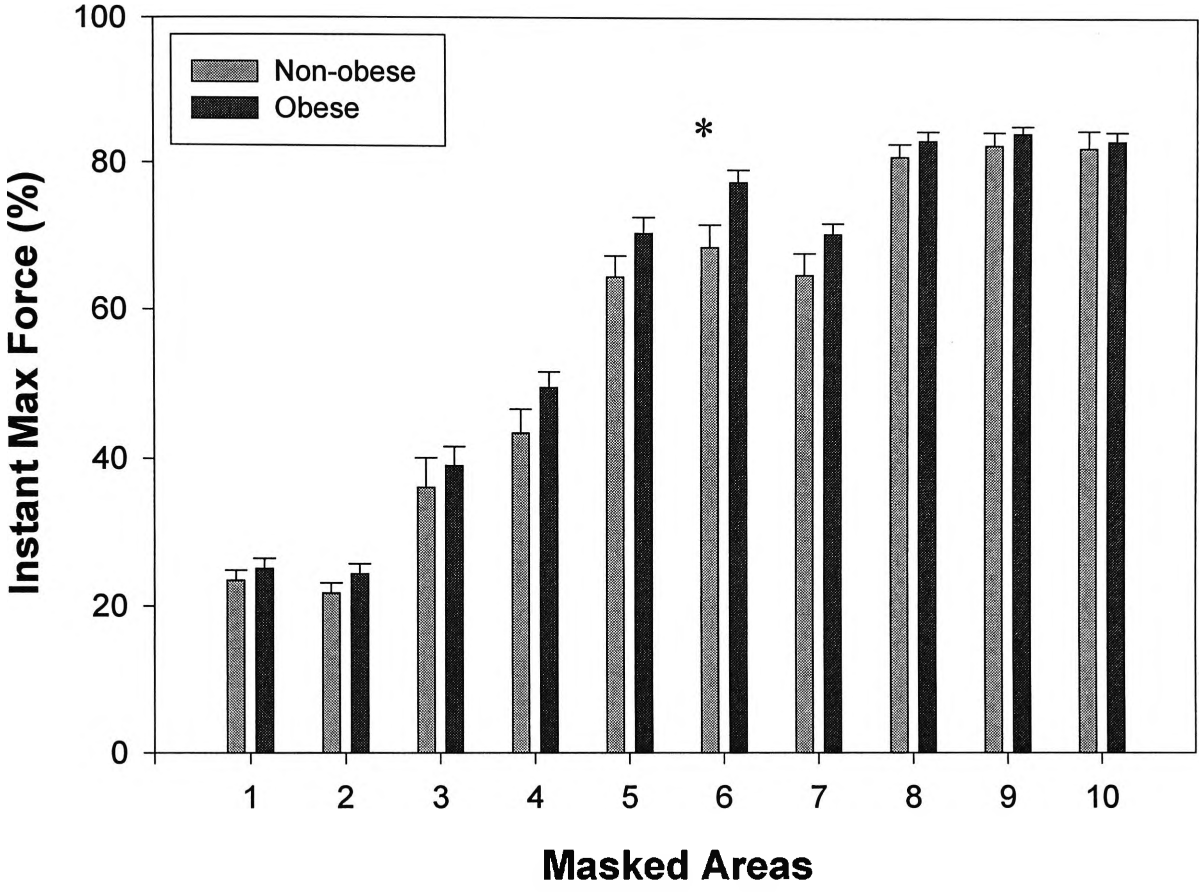

Figure 4.3 The instant in time during the roll-over-process when maximum force occurred in each of the 10 masks (means + standard errors) for the non-obese and obese children. * Denotes significant difference.

study by Hennig *et al.* (1991) the mean age of the children was 23 months whereas the age group of the children studied by Borges Machado & Hennig (1999) was 6 to 10 years of age.

Table 4.19 Percentage of the roll-over-process when maximum force occurred for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables	Non-obese				Obese			
	Left		Right		Left		Right	
(%)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total	47.83	25.0	46.91	19.0	52.78	17.9	56.33	18.3
Mask 1	22.85	5.9	24.22	7.2	24.69	5.9	25.47	6.7
Mask 2	20.23	4.9	23.35	7.5	23.81	7.3	25.01	5.7
Mask 3	34.99	19.0	37.32	17.8	37.79	12.2	40.42	11.2
Mask 4	41.27	17.7	45.69	10.9	48.40	10.3	50.85	8.2
Mask 5	67.17	12.1	62.08	13.6	68.68	9.7	72.50	10.3
Mask 6	68.04	16.4	69.33	12.0	77.06	8.8	78.14	6.3
Mask 7	64.78	16.5	64.96	10.7	71.36	5.9	69.62	7.3
Mask 8	77.42	8.9	84.76	5.5	83.69	5.5	82.97	6.3
Mask 9	81.70	9.2	83.61	6.7	83.96	5.3	84.72	4.1
Mask 10	80.00	12.7	84.55	7.7	83.31	6.7	83.12	5.1

When the test limb data were pooled, a significant main effect of obesity was found whereby the obese children generated higher mean force-time integrals for the whole foot*, Masks 1 and 2 (the medial and lateral heel), Masks 3 and 4 (the midfoot region), and Masks 6 and 7 (metatarsal heads 2 to 5) compared to the non-obese children (see Table 4.22 and Figure 4.4). That is, the force and the time that this force was generated over the heel, midfoot, and metatarsal heads was significantly higher in the obese children compared to the non-obese children.

* Post hoc analysis for force-time integrals found significant differences between the obese and non-obese children for the whole foot (q = 5.515), Mask 1 (q = 5.690), Mask 2 (q = 5.313), Mask 3 (q = 5.458), Mask 4 (q = 6.055), Mask 6 (q = 4.366) and Mask 7 (q = 5.612).

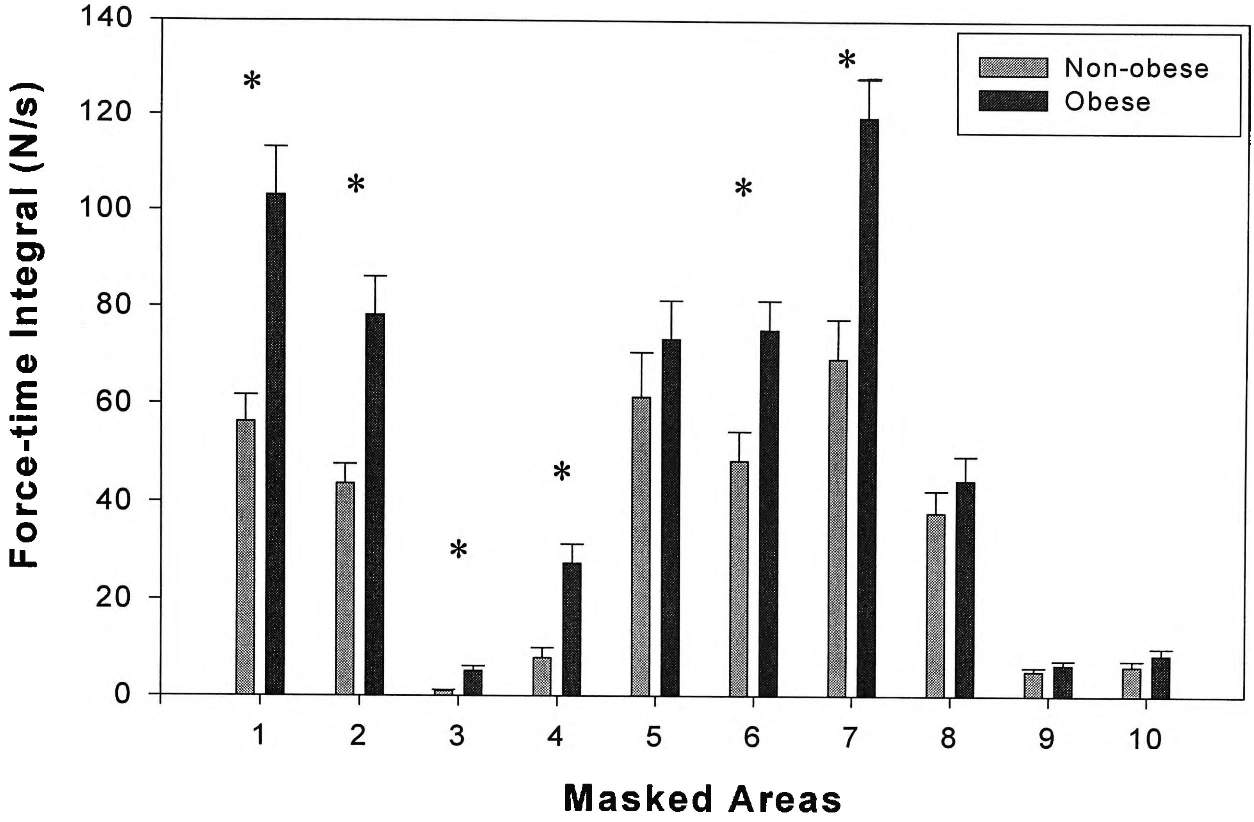

Figure 4.4 Force-time integral data for each of the 10 masks (means + standard errors) for the non-obese and obese children. * Denotes significant difference.

Table 4.20 F-ratios and p-values derived for each source of variance for the percentage of the roll-over-process when maximum force occurred with limb condition and the obesity factor.

Variable	Limb $F_{(1, 36)}$	Limb p-value	Obesity $F_{(1, 36)}$	Obesity p-value	Limb x Obesity $F_{(1, 36)}$	Limb x Obesity p-value
Total	0.042	0.838	1.258	0.270	0.121	0.730
Mask 1	0.280	0.600	0.574	0.454	0.021	0.885
Mask 2	1.124	0.296	1.647	0.208	0.220	0.642
Mask 3	0.259	0.614	0.366	0.549	<0.001	0.975
Mask 4	0.779	0.383	2.492	0.123	0.064	0.802
Mask 5	0.031	0.861	2.685	0.110	1.498	0.229
Mask 6	0.106	0.746	6.009	0.019*	<0.001	0.977
Mask 7	0.051	0.822	2.667	0.111	0.079	0.781
Mask 8	2.417	0.129	1.104	0.300	3.584	0.066
Mask 9	0.407	0.528	0.654	0.424	0.075	0.786
Mask 10	0.656	0.423	0.122	0.729	0.772	0.385

* Denotes significant difference at $p \leq 0.05$.

It was expected that the force-time integrals in the heel, midfoot and metatarsal head regions would be significantly higher in the obese children due to their increased mass (see Section 4.7.1 – 4.7.4). Force-time integrals are of interest in the present study as they have been related to fatigue of the bones of the foot (Fuller, 1996). The area of the obese child's foot most vulnerable to bony fatigue would therefore be the region encompassing the metatarsal heads, that is Masks 6 to 7. As the force-time integrals in Mask 7 were the highest recorded for an individual mask, it is postulated that this area of the foot may be at increased risk of potential trauma due to bony fatigue. To minimise this potential for bony fatigue, it is recommended that obese children wear a shoe, which can cushion the force-time integrals, particularly in the region of the metatarsal heads during physical activity.

Table 4.21 Force-time integrals in each mask for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables ($N{\cdot}s^{-1}$)	Non-obese				Obese			
	Left		Right		Left		Right	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total	334.48	137.6	341.60	139.2	549.73	181.8	535.56	196.8
Mask 1	53.94	20.6	58.63	28.1	103.60	45.0	102.73	46.8
Mask 2	39.74	14.8	47.74	20.8	75.78	35.7	80.73	38.0
Mask 3	1.02	1.2	0.89	0.8	5.44	5.7	4.86	3.6
Mask 4	6.78	7.7	9.07	11.3	26.31	16.2	28.59	19.6
Mask 5	61.87	46.4	61.43	37.4	80.11	43.7	66.95	27.9
Mask 6	48.74	27.3	48.34	28.3	80.27	29.4	70.68	25.2
Mask 7	70.03	33.8	69.05	42.4	119.50	39.9	120.28	43.6
Mask 8	40.17	22.5	35.92	18.8	44.12	15.7	45.03	27.7
Mask 9	5.55	4.4	4.79	2.5	6.16	2.5	6.90	5.0
Mask 10	6.64	5.9	5.75	5.2	8.45	4.8	8.81	7.8

4.7.7 Effects of Limb and Obesity on the Masked Regions for Contact Area

Descriptive statistics pertaining to the contact area in each mask during walking for the right and left feet of the obese and non-obese groups are presented in Table 4.23. Although, no study was located against which to directly compare these specific mask contact areas, David *et al.* (1999) reported values comparable to this study for heel, midfoot and forefoot contact areas for non-obese children.

In Table 4.24 it can be noted that a significant main effect of obesity was found for contact area for the whole foot and all the masks except Mask 8 (the hallux region), when the test limb data were pooled. That is, the obese children displayed a greater mean contact area for the whole foot and these masks compared to the non-obese children (see Figure 4.5). These findings suggest that the obese children have an increased foot contact area in 9 out of the 10 masked regions during gait, a finding consistent with the total foot contact area data presented in Sections 4.7.1, 4.7.2 and 4.7.3.

Table 4.22 F-ratios and p-values derived for each source of variance for the force-time integrals for each mask with limb condition and the obesity factor.

Variable	Limb $F_{(1, 36)}$	Limb p-value	Obesity $F_{(1, 36)}$	Obesity p-value	Limb x Obesity $F_{(1, 36)}$	Limb x Obesity p-value
Total	0.005	0.947	15.201	<0.001*	0.041	0.840
Mask 1	0.027	0.871	16.189	<0.001*	0.057	0.813
Mask 2	0.497	0.485	14.112	<0.001*	0.027	0.869
Mask 3	0.101	0.752	14.893	<0.001*	0.043	0.837
Mask 4	0.251	0.619	18.329	<0.001*	<0.001	1.000
Mask 5	0.296	0.589	0.906	0.348	0.260	0.614
Mask 6	0.328	0.570	9.531	0.004*	0.277	0.602
Mask 7	<0.001	0.993	15.748	<0.001*	0.005	0.945
Mask 8	0.060	0.808	0.911	0.346	0.142	0.708
Mask 9	<0.001	0.995	1.297	0.262	0.395	0.534
Mask 10	0.019	0.891	1.628	0.210	0.109	0.743

* Denotes significant difference at $p \leq 0.05$.

The increase in foot contact area of the obese children can be related back to Section 4.1 and 4.2 whereby these children had a larger foot shape and foot structural dimensions. This increased foot contact area in the midfoot region may also be due to the presence of a fat pad in this region of the feet of the obese child, that is no longer present in normal mass children. Such a fat pad may be an adaptive response to assist obese children cushion the higher forces associated with their increase mass or merely another site of increased adiposity that has little functional significance. Alternatively, this increased midfoot contact area may represent structural deformity of the obese children's feet indicative of collapsed longitudinal arches and the foundation for future pathologies. As the mechanism of this increased midfoot contact area is purely speculative, further research pertaining to the causes of increased midfoot contact areas in obese children is recommended. Irrespective of the mechanism, how this increased foot contact area moderates the higher force values in each mask becomes evident when the pressure results are presented in the following sections.

Table 4.23 Contact area in each mask for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables	**Non-obese**				**Obese**			
	Left		**Right**		**Left**		**Right**	
(cm^2)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Total	80.49	14.0	82.35	12.3	110.57	23.2	111.06	22.4
Mask 1	11.40	1.7	10.93	1.9	13.87	2.7	14.16	2.9
Mask 2	11.13	1.9	11.26	2.0	13.72	2.8	14.08	2.7
Mask 3	1.44	1.3	1.55	1.5	4.12	4.4	4.16	3.9
Mask 4	8.18	6.1	9.20	6.7	16.47	5.9	17.52	5.2
Mask 5	10.45	2.5	10.73	2.2	13.12	2.9	12.72	2.1
Mask 6	8.13	1.1	8.26	1.6	10.51	2.0	10.04	1.9
Mask 7	15.44	2.4	15.57	2.4	19.63	3.6	20.35	3.5
Mask 8	7.91	1.7	8.04	1.4	9.48	1.8	8.96	2.9
Mask 9	2.46	0.9	2.65	0.7	3.15	0.8	3.03	0.6
Mask 10	4.33	1.9	4.12	1.8	6.46	1.6	6.03	1.8

4.7.8 The Effect of Limb and Obesity on the Masked Regions for the Length of Time of the Roll-Over-Process

Descriptive statistics pertaining to length of time spent in each mask relative to the roll-over-process for the right and left feet of the obese and non-obese groups are presented in Table 4.25. No study could be located against which direct comparisons could be made with children of normal mass for the masked regions.

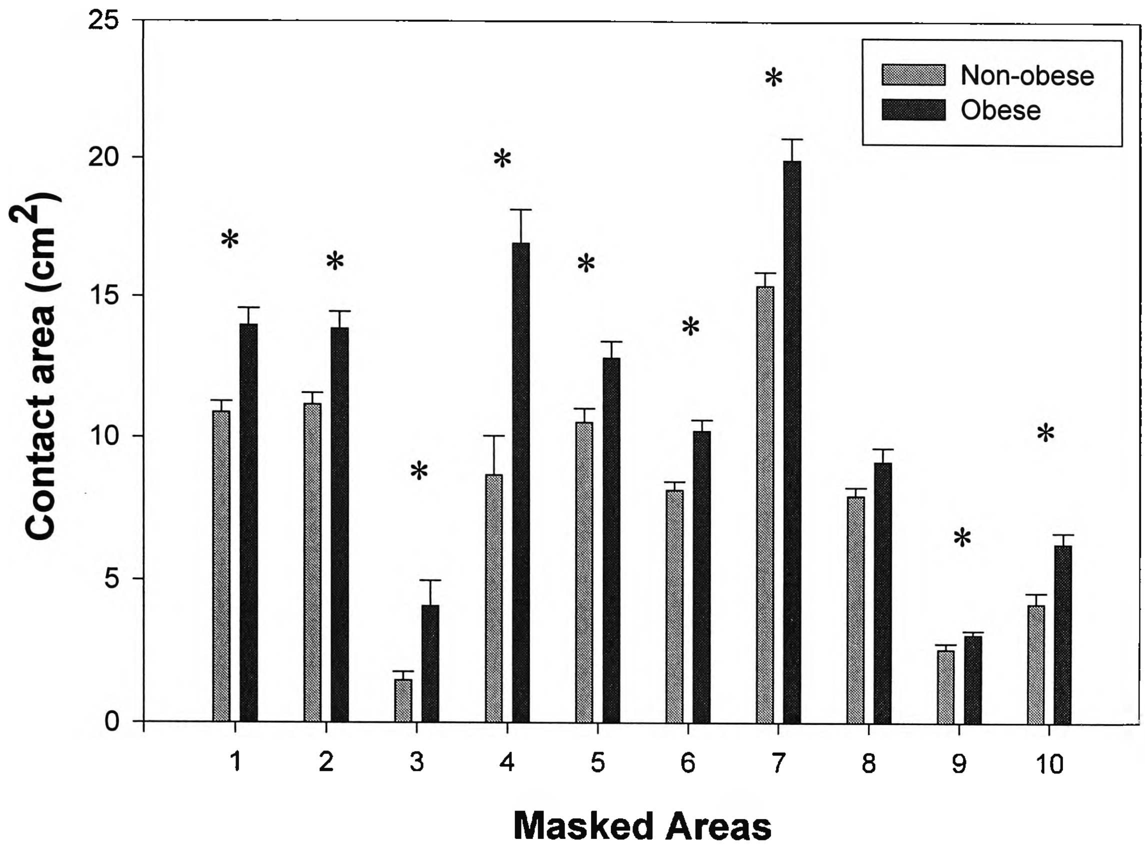

Figure 4.5 Contact area data for each of the 10 masks (means + standard errors) for the non-obese and obese children. * Denotes significant difference.

Table 4.24 F-ratios and p-values derived for each source of variance for the contact area for each masked region with limb condition and the obesity factor.

Variable	Limb		Obesity		Limb x Obesity	
	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value
Total	0.040	0.844	24.921	<0.001*	0.013	0.909
Mask 1	0.015	0.903	16.657	<0.001*	0.072	0.790
Mask 2	0.112	0.739	13.310	<0.001*	0.023	0.882
Mask 3	0.006	0.941	7.283	0.011*	0.002	0.967
Mask 4	0.296	0.590	19.163	<0.001*	<0.001	0.994
Mask 5	0.006	0.941	9.168	0.005*	0.191	0.665
Mask 6	0.094	0.760	15.492	<0.001*	0.322	0.574
Mask 7	0.196	0.660	21.812	<0.001*	0.094	0.761
Mask 8	0.091	0.764	3.798	0.059	0.254	0.617
Mask 9	0.019	0.891	5.283	0.027*	0.451	0.506
Mask 10	0.315	0.578	12.884	<0.001*	0.0384	0.846

* Denotes significant difference at $p < 0.05$.

Significant main effects of obesity were found for Mask 3 and Mask 4 when the data were pooled across test limbs (see Table 4.26). That is, the obese children spent a longer mean percentage of the roll-over-process in the midfoot region (Mask 3 q = 3.991; and Mask 4 q = 4.516) compared to their non-obese counterparts (see Figure 4.6). It was expected that the obese children would spend a longer percentage of the roll-over-process in the midfoot area region as these children have flatter feet which were in contact with the ground for longer when walking (see Section 4.7.7). However, the absence of temporal differences for the other regions of the foot indicate that both obese and non-obese children spent a similar amount of time in contact with the platform when walking. This is consistent with findings reported by Hennig *et al.* (1998) where there was no difference between the roll-over-process of overweight and non-overweight adults and by Hills *et al.* (1991) whereby there was no difference in the stance phase duration between obese and non-obese children (see Section 2.4).

Table 4.25 Length of time spent in each mask during the roll-over-process for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables	Non-obese				Obese			
	Left		Right		Left		Right	
(%)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total (ms)	702.00	144.0	732.00	149.2	741.27	111.4	723.73	128.2
Mask 1	56.24	13.5	57.19	11.9	60.97	7.5	62.73	6.9
Mask 2	55.12	13.6	55.97	11.4	60.50	7.3	62.20	7.2
Mask 3	30.59	16.2	35.05	18.9	46.31	13.8	46.75	11.4
Mask 4	50.93	21.6	54.72	10.0	65.63	7.7	65.94	5.8
Mask 5	85.79	8.0	84.98	9.5	85.29	5.4	82.45	5.4
Mask 6	86.12	8.0	84.83	9.1	88.26	5.8	84.04	4.8
Mask 7	88.82	5.6	85.21	8.8	88.44	5.7	85.60	4.3
Mask 8	78.73	16.9	78.05	11.6	78.33	7.8	68.08	21.2
Mask 9	62.98	19.8	64.05	17.5	71.47	11.3	64.68	13.5
Mask 10	66.37	16.7	70.24	10.4	75.33	15.3	66.61	11.9

4.7.9 Effects of Limb and Obesity on the Masked Regions for Peak Pressure

Means and standard deviations pertaining to the peak pressure recorded in each mask for the right and left feet of the obese and non-obese groups are presented in Table 4.27. Comparing peak pressure data recorded for masked regions of the foot is difficult due to the wide variation among studies with respect to how the foot is subdivided into discrete masks, and variations in the pressure measurement systems used. For example, Borges Machado & Hennig (1999) reported peak pressure values for children of normal body mass that were slightly lower than the data recorded for non-obese children in this study. These between-study differences, however, are most likely a consequence of different pressure measurement systems where Borges Machado & Hennig (1999) used the PEDAR in-shoe system and not a platform. Hennig *et al.* (1994) also reported slightly lower peak pressure values than the data in the current study, despite using a pressure platform to obtain their data. However, Hennig *et al.* (1994) only used eight masks to characterise the foot. In contrast, peak pressure values reported by David *et al.*

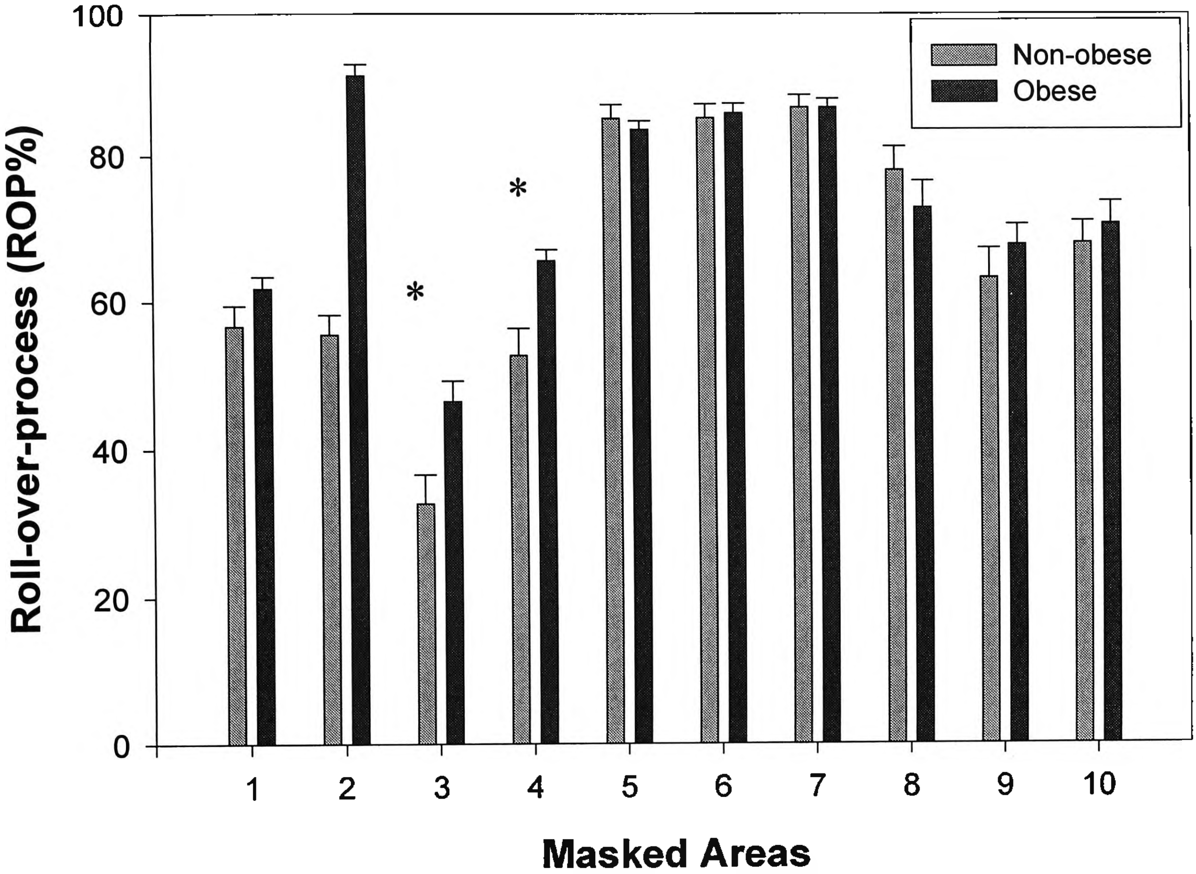

Figure 4.6 The length of time spent in each mask during the roll-over-process (means + standard errors) for the non-obese and obese children.
* Denotes significant difference.

Table 4.26 F-ratios and p-values derived for each source of variance for the length of time spent in each mask during the roll-over-process with limb condition and the obesity factor.

Variable (%)	Limb $F_{(1, 36)}$	Limb p-value	Obesity $F_{(1, 36)}$	Obesity p-value	Limb x Obesity $F_{(1, 36)}$	Limb x Obesity p-value
Total (ms)	0.022	0.884	0.134	0.717	0.315	0.578
Mask 1	0.170	0.682	2.469	0.125	0.015	0.903
Mask 2	0.154	0.697	3.217	0.081	0.017	0.896
Mask 3	0.254	0.617	7.966	0.008*	0.170	0.682
Mask 4	0.256	0.616	10.198	0.003*	0.184	0.670
Mask 5	0.630	0.433	0.435	0.514	0.196	0.660
Mask 6	1.490	0.230	0.089	0.767	0.424	0.519
Mask 7	2.608	0.115	<0.001	0.997	0.037	0.848
Mask 8	1.282	0.265	1.157	0.289	0.986	0.327
Mask 9	0.324	0.573	0.823	0.370	0.612	0.439
Mask 10	0.310	0.581	0.373	0.545	2.056	0.157

* Denotes significant difference at $p \leq 0.05$.

(1999) were comparable with the results of non-obese children in this study although the foot was only divided into three masks. Irrespective of between-study differences in the absolute pressure data, the pattern of pressure distribution displayed by the children in the present study when walking was similar to previous studies. For example, the regions of the foot that generated the lowest pressure values were Mask 3 and 4, the midfoot region, a finding previously reported by Hennig *et al.* (1991). The highest readings were recorded for Mask 1, the medial heel of the foot and Mask 8, the hallux.

Significant main effects of obesity were found for Masks 3 and 4, and Masks 6 and 7 when the data were pooled across test limbs (see Table 4.28 and Figure 4.7). That is, the obese children generated greater mean peak pressures in Mask 3 (q = 6.530) and Mask 4 (q = 4.590), the midfoot, and Mask 6 (q = 4.138) and Mask 7 (q = 4.191), metatarsal head 2 and metatarsal heads 3 to 5, respectively, compared to their non-obese counterparts.

Table 4.27 Dynamic peak pressure in each mask for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables	Non-obese				Obese			
	Left		Right		Left		Right	
($N \cdot cm^{-2}$)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total	75.13	21.2	80.13	25.6	85.67	21.3	89.72	29.4
Mask 1	57.64	11.1	63.34	26.1	69.83	20.7	66.62	21.0
Mask 2	49.22	10.2	54.48	19.5	56.60	11.7	56.31	15.7
Mask 3	6.54	4.9	5.72	3.8	13.23	5.7	13.53	5.3
Mask 4	9.48	5.1	10.23	7.2	15.21	6.3	16.61	4.8
Mask 5	40.72	25.8	44.58	29.4	41.72	15.6	43.06	22.5
Mask 6	36.45	21.0	32.49	11.6	53.10	19.9	51.15	21.9
Mask 7	39.90	15.8	33.83	10.5	50.89	15.8	52.67	20.1
Mask 8	57.34	28.6	71.96	30.6	68.61	26.9	70.47	42.5
Mask 9	22.53	15.9	20.68	5.1	24.19	9.6	27.52	18.1
Mask 10	16.81	13.8	17.76	12.1	16.95	7.4	16.88	13.4

Similar to the present results David *et al.* (1999) reported that greater midfoot pressures were generated by obese children compared to their leaner counterparts. The increase in midfoot pressures displayed by the obese children is more than likely a consequence of the unique structural characteristics of their feet discussed previously (see Section 4.1 and 4.2). That is, as the obese children have flatter feet, the medial midfoot region of the foot contacts the pressure platform, generating pressure readings in this area of the foot. In contrast, few of the non-obese children's higher arched feet made contact with the platform in the medial midfoot region, thereby resulting in the lower pressures observed. However, these increased pressures experienced by the obese children in the medial midfoot area are relatively low compared to other areas of the foot and therefore not of major concern.

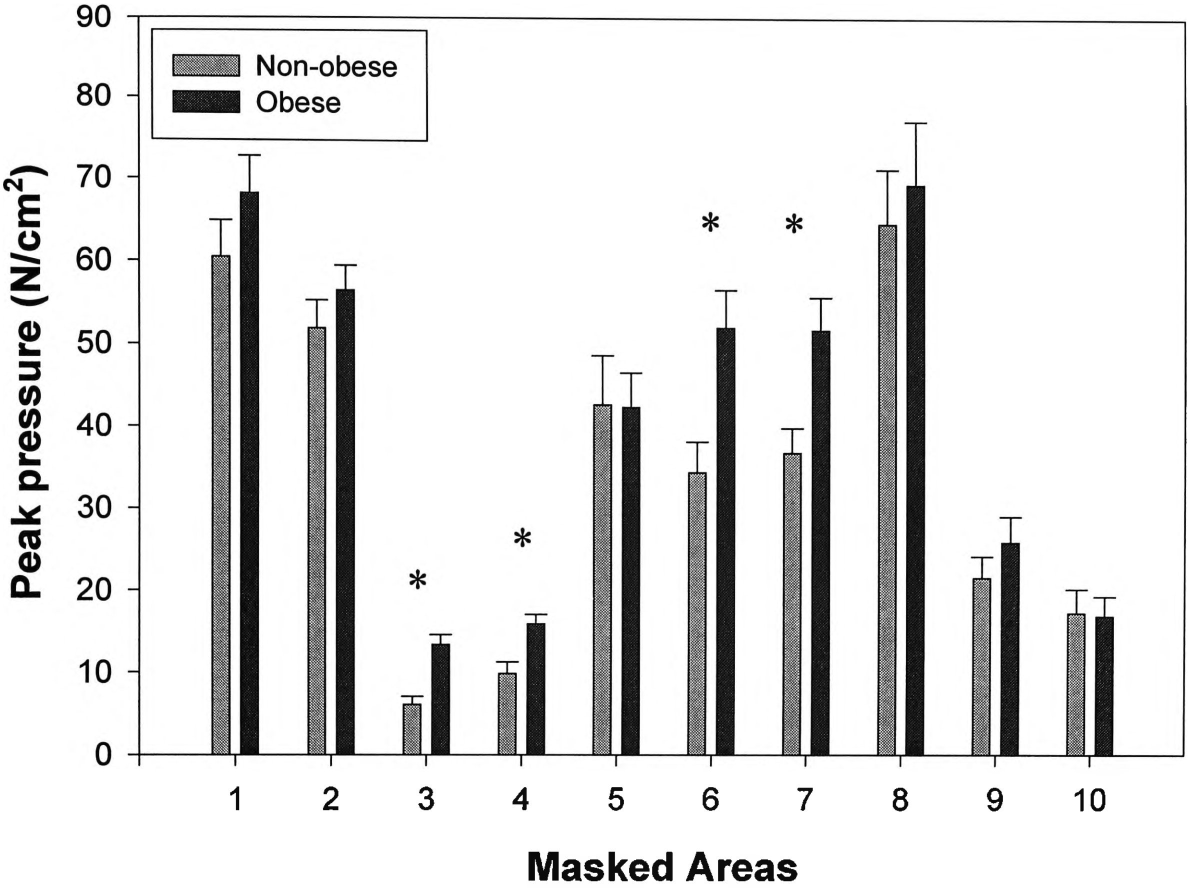

Figure 4.7 Peak pressures in each of the 10 masked areas (means + standard errors) for the non-obese and obese children. * Denotes significant difference.

Table 4.28 F-ratios and p-values derived for each source of variance for the peak pressure in the masks with limb condition and the obesity factor.

Variable	Limb		Obesity		Limb x Obesity	
	$F_{(1,36)}$	p-value	$F_{(1,36)}$	p-value	$F_{(1,36)}$	p-value
Total	0.338	0.565	1.673	0.204	0.004	0.951
Mask 1	0.037	0.848	1.427	0.240	0.474	0.496
Mask 2	0.284	0.598	0.976	0.330	0.354	0.555
Mask 3	0.027	0.870	21.317	<0.001*	0.130	0.721
Mask 4	0.330	0.569	10.535	0.003*	0.031	0.861
Mask 5	0.119	0.732	0.001	0.973	0.028	0.868
Mask 6	0.240	0.627	8.562	0.006*	0.028	0.869
Mask 7	0.182	0.672	8.780	0.005*	0.609	0.440
Mask 8	0.633	0.431	0.223	0.640	0.379	0.542
Mask 9	0.032	0.860	1.033	0.316	0.381	0.541
Mask 10	0.014	0.908	0.009	0.924	0.018	0.893

* Denotes significant difference at $p \leq 0.05$.

Conversely, the higher peak pressure results generated for Mask 6 and 7 by the obese children are of concern due to their relatively high values. Futhermore, these results now provide more specific information about where in the forefoot higher pressures are being experienced by obese children than could be shown by the previous forefoot pressure analysis (see Section 4.7.3). As these higher pressures are being experienced on smaller bony and ligamentous structures surrounding metatarsal heads 2 to 5, this potentially may have negative consequences for the feet of the obese child, in terms of an increased risk of forefoot pathologies, such as stress fractures of the metatarsal bones and ulcerations in diabetic patients. Dowling *et al.* (2001) also postulated that obese children might experience foot discomfort associated with increased forefoot plantar pressures, which if severe enough, may discourage them from being physically active and thereby perpetuate the cycle of obesity. For this reason, and to minimise the risk of metatarsal head stress fractures, it is recommended that shoes designed for obese children need additional cushioning placed under the region supporting the metatarsal heads 2 to 5 to help dissipate the higher pressures generated during gait.

4.7.10 Effects of Limb and Obesity on the Masked Regions for Instant in Time of the Roll-Over-Process at which Peak Pressure Occurred

Means and standard deviations pertaining the instant in time, as a percentage of the roll-over-process, at which the peak pressure occurred in each mask for the right and left feet of the obese and non-obese groups are presented in Table 4.29. These values reflect the characteristic temporal aspects of weight distribution during the stance phase of the gait cycle whereby peak pressures are initially experienced in Masks 1 and 2, the medial and lateral aspect of the heel, progressing through the midfoot to push-off with Masks 8, 9 and 10 representing the toes.

Table 4.29 Instant in time as a percentage of the roll-over-process when the peak pressure occurred for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables	Non-obese				Obese			
	Left		Right		Left		Right	
(%)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total	58.59	19.2	61.19	28.8	48.88	30.0	57.47	22.3
Mask 1	16.10	6.8	20.76	8.3	19.24	7.8	18.43	6.4
Mask 2	17.51	5.7	20.45	8.2	19.78	7.4	17.96	5.4
Mask 3	31.46	17.0	32.05	14.5	31.85	9.9	35.32	7.8
Mask 4	39.56	16.2	39.04	10.1	42.29	13.7	45.59	8.9
Mask 5	72.86	13.0	66.34	16.0	75.95	11.2	75.04	11.8
Mask 6	77.07	14.8	74.13	10.6	83.99	6.3	84.72	4.0
Mask 7	73.18	18.5	72.12	12.3	80.33	4.5	79.07	6.4
Mask 8	75.39	11.1	82.46	8.4	82.17	7.8	81.23	6.5
Mask 9	81.87	9.5	83.96	6.1	84.24	5.2	84.46	3.8
Mask 10	80.40	12.9	85.66	6.3	84.04	7.9	79.06	8.0

A significant main effect of obesity was found for Mask 6, metatarsal head 2, when the test limb data were pooled (see Table 4.30). That is, the obese children generated mean peak pressures in Mask 6 (q = 3.989) later during the roll-over-process compared to the non-obese children (see Figure 4.8 and Table 4.30). This result would suggest that rather than displaying the typical pattern of pressure transfer through the stance phase described previously, the obese children formed a relatively rigid lever to push the foot off the ground later in gait. That is, the obese children generated the propulsive forces using the metatarsal heads and toe regions of the foot as a combined unit at relatively the same percentage of the roll-over-process. This finding may reflect excessive pronation in individuals with flatfeet whereby there is a medial shift in body mass hindering the development of a propulsive lever at toe-off (Bauer *et al.*, 1996). The obese child may have difficulties developing the propulsive lever and therefore just lift their foot in order to attain foot clearance in the swing phase of the gait cycle. If this is happening in the obese child, intervention strategies in the form of foot and leg exercises may help the development of a propulsive lever during toe-off in gait for these children.

Table 4.30 F-ratios and p-values derived for each source of variance for the instant in time as a percentage of the roll-over-process when peak pressure occurred with limb condition and the obesity factor.

Variable	**Limb**		**Obesity**		**Limb x Obesity**	
	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value	$F_{(1, 36)}$	p-value
Total	0.482	0.492	0.694	0.410	0.138	0.712
Mask 1	0.685	0.413	0.030	0.863	1.390	0.246
Mask 2	0.069	0.795	0.003	0.960	1.232	0.274
Mask 3	0.249	0.621	0.204	0.654	0.125	0.725
Mask 4	0.121	0.729	1.359	0.251	0.231	0.634
Mask 5	0.800	0.377	2.021	0.164	0.457	0.503
Mask 6	0.127	0.724	7.957	0.008*	0.348	0.559
Mask 7	0.096	0.758	3.571	0.067	<0.001	0.978
Mask 8	1.266	0.268	1.037	0.315	2.163	0.150
Mask 9	0.317	0.577	0.485	0.490	0.205	0.654
Mask 10	0.002	0.961	0.267	0.609	3.180	0.083

* Denotes significant difference at $p \leq 0.05$.

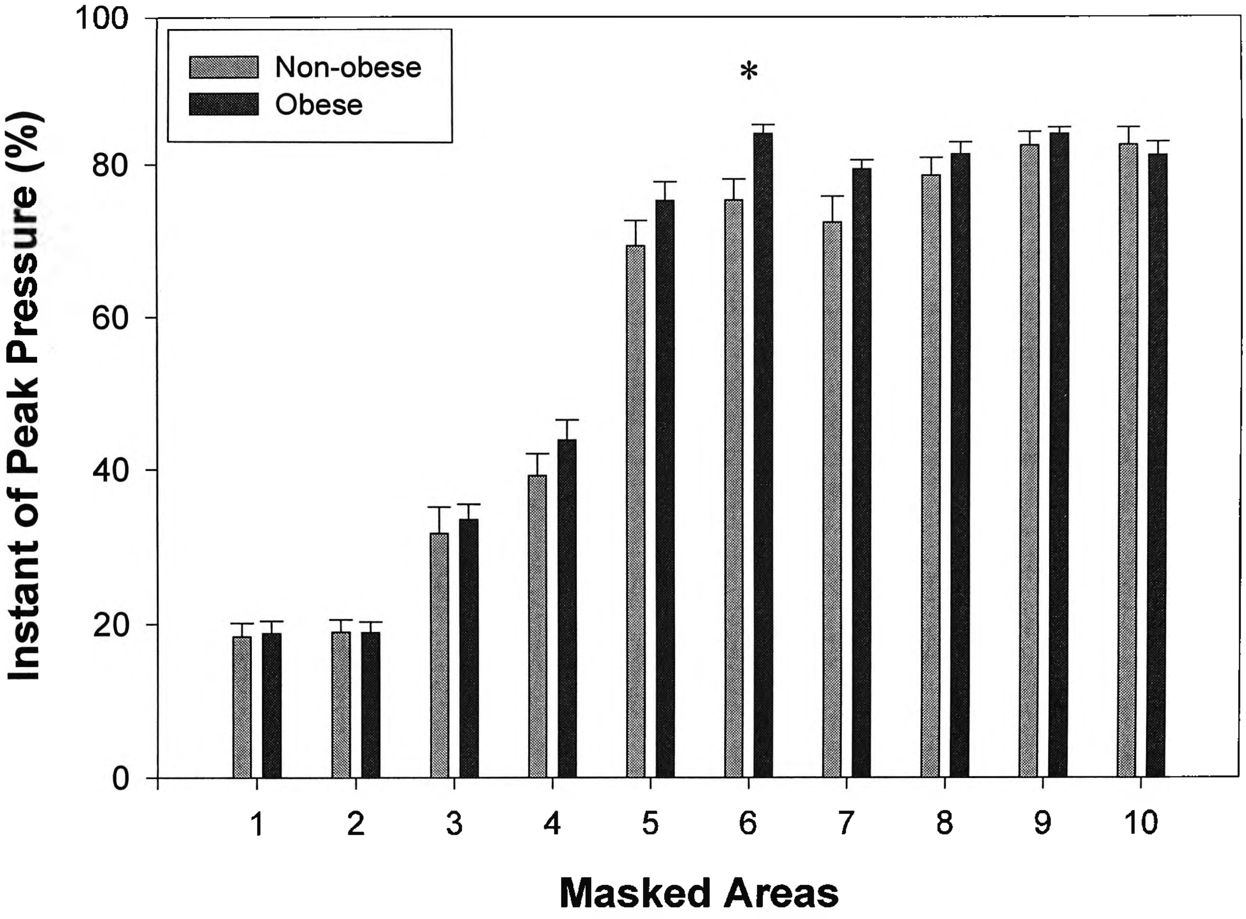

Figure 4.8 Instant in time when peak pressure occurred during the roll-over-process for each of the masks (means + standard errors) for the non-obese and obese children. * Denotes significant difference.

4.7.11 Effects of Limb and Obesity on the Masked Regions for Pressure-Time Integrals

Descriptive statistics pertaining to the pressure-time integrals in each mask for the right and left feet of the obese and non-obese groups are presented in Table 4.31. No study at the present time could be located against which to compare the present values.

Table 4.31 Pressure-time integrals in each mask for the left and right feet of the non-obese (n = 10) and obese (n = 10) subjects.

Variables ($N{\cdot}scm^{-2}$)	Non-obese				Obese			
	Left		Right		Left		Right	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Total	32.69	13.3	35.80	19.5	36.99	10.0	38.39	13.6
Mask 1	12.66	5.1	14.80	7.4	17.76	6.5	17.89	7.7
Mask 2	10.95	4.2	12.77	5.7	15.28	5.2	15.51	6.5
Mask 3	1.15	1.0	1.07	0.7	3.46	2.0	3.42	2.1
Mask 4	2.11	1.2	2.53	1.5	5.09	2.4	5.31	2.0
Mask 5	15.13	10.8	16.13	12.6	14.73	7.7	13.36	5.9
Mask 6	13.28	8.3	11.84	5.3	16.10	4.4	14.47	4.6
Mask 7	13.01	5.7	11.83	5.3	15.99	4.1	16.08	6.6
Mask 8	17.39	10.5	18.95	13.6	17.34	5.9	17.63	10.9
Mask 9	5.75	4.9	5.10	2.4	5.76	2.1	6.57	5.1
Mask 10	4.63	4.2	4.57	3.7	4.51	2.4	4.77	3.9

A significant main effect of obesity was found for the pressure-time integrals in Masks 2 to 4 and Mask 7 whereby the obese children displayed higher mean pressure time integrals in Mask 2 ($q = 2.884$), Mask 3 ($q = 6.625$), Mask 4 ($q = 6.937$) and Mask 7 ($q = 2.951$) compared to the non-obese children (see Table 4.32 and Figure 4.9). As the pressure-time integrals in Masks 3 and 4 were relatively low they were not considered highly problematic. However, as these results reflect the time over which pressure is exerted in these masks, they suggest that the heel and metatarsal heads 2 to 5 of the obese children's feet may be at risk from trauma as these values are relatively high. For example, the high pressure-time integrals under the metatarsal heads 3 to 5 suggest that over time trauma to the skin in this region could potentially occur, as high pressure-time integrals have been associated with ulcerations in diabetic patients (Kosiak, 1959; Drerup *et al.*, 2000). Based on these findings it is imperative that intervention strategies need to be developed to help decrease these higher pressure-time integrals experienced by the obese child especially under metatarsal heads 3 to 5. One possible strategy to consider is the development of foot and leg exercises in order to alter the way in which obese children load their feet during gait or appropriate shoe design to help dissipate these high pressures.

Table 4.32 F-ratios and *p*-values derived for each source of variance for the pressure-time integrals in each of the masks with limb condition and the obesity factor.

Variable	Limb		Obesity		Limb x Obesity	
	$F_{(1, 36)}$	*p*-value	$F_{(1, 36)}$	*p*-value	$F_{(1, 36)}$	*p*-value
Total	0.241	0.626	0.565	0.457	0.0346	0.853
Mask 1	0.281	0.599	3.668	0.063	0.221	0.641
Mask 2	0.353	0.556	4.157	0.049*	0.212	0.648
Mask 3	0.0146	0.904	21.944	<0.001*	0.002	0.969
Mask 4	0.304	0.585	24.063	<0.001*	0.029	0.865
Mask 5	<0.001	0.953	0.272	0.605	0.152	0.699
Mask 6	0.691	0.411	2.174	0.149	0.003	0.960
Mask 7	0.100	0.754	4.353	0.044*	0.133	0.718
Mask 8	0.076	0.785	0.0422	0.838	0.037	0.849
Mask 9	<0.001	0.951	0.364	0.550	0.346	0.560
Mask 10	0.007	0.932	0.00112	0.974	0.018	0.894

* Denotes significant difference at $p \leq 0.05$.

Furthermore, the higher forces and force-time integrals generated by the obese child could not be sufficiently compensated by the increases in foot contact area therefore causing increases in pressure and pressure-time integrals. These higher pressure and pressure-time integrals are of major importance as they may indicate potential areas at risk of trauma in the foot.

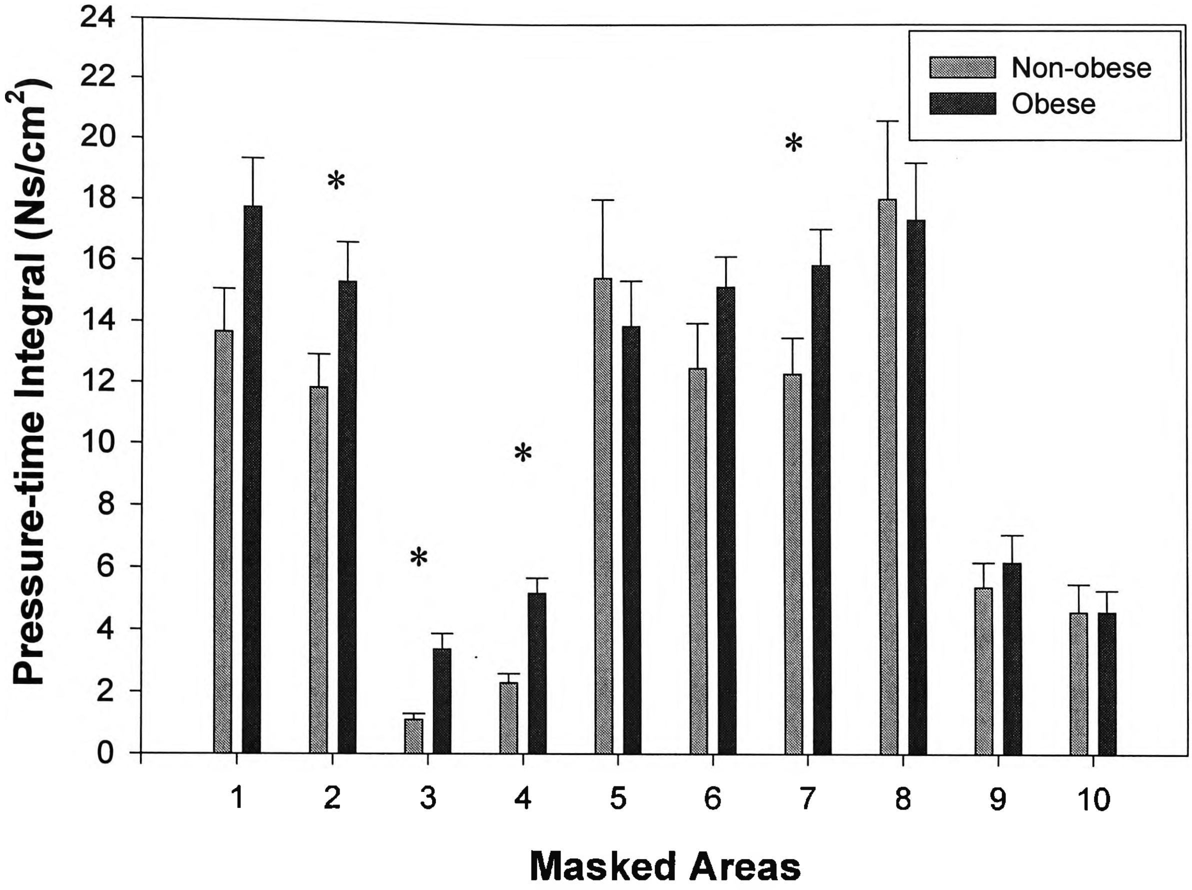

Figure 4.9 Pressure-time integral data for each of the 10 masked regions (means + standard errors) for the non-obese and obese children. * Denotes significant difference.

Chapter 5
Summary and Conclusions

5.0 Summary of the Results

Childhood obesity is a growing worldwide concern that needs to be urgently addressed as obese children tend to become obese adults. The increased mass associated with obesity increases the risk of developing musculoskeletal pathologies. Foot pathologies in the obese child have not been widely investigated although obese children have been found to have flatter feet and experience higher forefoot pressure when compared with their non-obese counterparts. There are many questions, however, relating to the foot structure and function of obese children, which have yet to be investigated. Therefore, the purpose of the present study was to investigate the effects of obesity on foot structure and function, foot sensation and plantar pressure distributions in children. This was achieved by quantifying foot structure and function characteristics of obese and non-obese children including (i) anthropometric measurements, (ii) footprint parameters obtained using a pedograph, (iii) sensory stimuli to quantify plantar sensations, (iv) rearfoot alignment and motion and (v) static and dynamic peak forces, areas and pressures.

In accordance with Hypothesis 1 (see Section 1.3), results of the present study indicated that obese children displayed significantly broader feet then the non-obese children. Increased ball of foot circumferences, ball of foot diagonal breadths, ball of foot horizontal breadths and heel breadths in the obese child confirmed this hypothesis and clearly showed how the foot shape and dimensions of the obese children's feet differ markedly from the feet of children of normal mass. Furthermore, results of the present study indicated that obese children displayed flatter feet than their non-obese counterparts, again supporting Hypothesis 1. This was confirmed by a trend whereby the obese children displayed a decreased FA, combined with a significantly increased CSI and AI, and an increased foot contact area, both statically and dynamically, as derived from the AT-4® system, compared to their non-obese counterparts. As there are many differences in the structural characteristics of the feet of obese children, it is recommended that a shoe last be developed to cater for the specific and unique characteristics of the feet of obese children.

In contrast to Hypothesis 2, there was no significant difference in the plantar sensations experienced by the obese and non-obese children. This was revealed when the obese and non-obese children reached the same criteria to detect both pressure and vibration. Therefore, it would appear that long term bearing of excessive body mass does not compromise children's ability to detect plantar sensations, although it is recommended that further research is required in this area.

In accordance with Hypothesis 3, there was no difference in the static rearfoot alignment displayed by the obese and non-obese children when they were tested in three different standing positions, although it was noted that standing position significantly affected rearfoot alignment results. Therefore, it is postulated that the position of the feet affects static rearfoot alignment rather than increased body mass *per se*.

Contrary to Hypothesis 4, no significant differences were found between the obese and non-obese children during gait for rearfoot motion, although a difference of test limb was found. As data in the present study were restricted to a two-dimensional analysis it is recommended that rearfoot motion be re-examined undertaking a three-dimensional analysis.

In agreement with Hypothesis 5, the dynamic forefoot pressures generated by the obese subjects when walking were higher than the forefoot pressures generated by non-obese subjects. That is, the increase in forefoot contact area was not sufficient to compensate for the higher forces experienced by the obese children. Obese children also generated higher pressures statically even though these higher forces were generated over a larger area. More specifically, the peak pressures and pressure-time integrals were significantly higher in the regions of the obese child's foot under the metatarsal heads 2 to 5. This finding suggests that obese children might be at an increased risk of developing foot pathologies, such as stress fractures in the forefoot, or skin ulcerations as a result of increased pressures being borne by the small bones of the forefoot. Based on these findings it is recommended that specific footwear is developed for obese children to cater for their unique foot shape while providing the necessary cushioning under the second to fifth metatarsal heads in order to decrease pressures in these potentially vulnerable areas. Intervention strategies including leg and foot exercises should also be developed to help obese children use their feet more efficiently as propulsive levers during gait.

5.1 Conclusions and Implications of this Study

Although obesity appears to have no effect on plantar sensations or static rearfoot alignment, structurally, the feet of the obese child are broader, higher and thicker than the feet of the non-obese children. Furthermore, in young children long-term bearing of excessive mass caused by obesity appears to flatten the medial midfoot region, increasing the area and time this region of the foot contacts the ground. Functionally, obese children generated higher dynamic pressures and pressure-time integrals under their metatarsal heads 2 to 5 when walking and thereby may be at an increased risk of developing foot pathologies or foot discomfort in this area of the foot. As the long-term consequences of these increased dynamic pressures are unknown for obese children, it is recommended that the feasibility of developing footwear specific to the unique structural and functional characteristics of the obese child's foot be investigated. The development of a shoe specifically for this population should be based on the unique characteristic features of obese children's foot shape, their increased foot contact area and the need for adequate forefoot cushioning to help decrease the pressures generated under the second to fifth metatarsal heads. Such footwear would ensure that obese children can comfortably participate in physical activities and, in turn, halt the cycle of obesity.

5.2 Recommendations for Future Study

The following recommendations are presented as guidelines for future research into the area of childhood obesity and foot structure and/or function:

1. The changes in foot structure associated with obesity need to be fully investigated to determine whether flatfootedness is associated with structural

dysfunction of the longitudinal arches from bearing excessive mass or whether a fat pad is present in the midfoot region of obese children.

2. The long-term effects of obesity on foot structure and function at present are unknown. Therefore, a longitudinal study is required to establish whether there are indeed negative consequences of increased mass on foot structure and function, including foot sensation.
3. Additionally, it is unknown whether the current changes noted in foot structure and function for obese children can be reversed through reductions in mass. Therefore, a study is required to investigate the effects of a mass reduction strategy on foot structure and function in children.
4. A three-dimensional analysis should be undertaken to determine whether obesity affects rearfoot motion in children, as findings from this current study were inconclusive.

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Appendix 1 Parent Information Package

Project Title

FOOT PRESSURE, FOOT STRUCTURE AND SENSORY FOOT FUNCTION IN CHILDREN

Project Objectives

As adults, we quite often suffer foot problems such as painful feet, and flattened arches. These problems may develop as early as during childhood. However, we know very little about how problems in children's feet may develop or about the range in size, shape, patterns of pressure areas and sensation in children's feet. We therefore want to examine feet (and height and weight as they affect feet) in a group of "normal" children, some of which will be overweight.

Test Procedures

For the study your child's height and weight will firstly be measured. Your child's feet will then be assessed by a podiatrist to look at their foot structure and function. Your child's footprints will then be recorded on paper to see how much of their feet touch the ground when they are standing still. Your child will then step onto and walk over a pressure mat several times. This pressure mat will record the pressure that they feel on the soles of their feet. While standing and walking your child will be videoed from the back and the side to look at their gait and posture. The second part of the experiment involves assessing what your child's foot can feel when they are gently touched with a tickling "stick". The total time involved for testing will be approximately one hour.

Risks and Discomforts

This study involves virtually no risk or discomfort; they should find it an interesting experience.

Enquiries

Any questions about the procedures and/or rationale in this investigation are welcome at any time. Please ask for an explanation of any point which you do not understand, or which you feel is not clear. Your initial contact person is the investigator conducting this research, Annaliese Dowling (phone (02) 4221 3881). Subsequent enquiries may be made to Dr Julie Steele (Supervising Lecturer, Department of Biomedical Science, University of Wollongong: phone (02) 4221 3881). Any enquiries on the conduct of this experiment may be directed to the Secretary of the University of Wollongong Human Experimentation Ethics Committee (Karen McRae) on (02) 4221 4457.

Freedom of Consent

Participation in this study is entirely on a voluntary basis. You are free to withdraw your child from the study before or during the experiment, and your child is likewise free to withdraw. You and your child's participation and/or withdrawal will not influence you and your child's involvement with the University of Wollongong, Kidfit or Kinross Wolaroi School.

Confidentiality

All questions, answers and results of this study shall be treated with absolute confidentiality. Children will be identified in the resultant manuscripts, reports or publications by the use of subject codes only.

Appendix 2 Child Information Sheet

Looking at Feet in Children

What are we trying to do?

- We want to look at your feet when you are standing still and when you are walking. We also want to see what the bottom of your feet feel.

What are we going to do?

- We will find out how tall you are and how much you weigh. Then we will look at your feet and see what they feel when they are touched by a tickling "stick". You will stand on a mat so we can make a footprint of your feet. Then you will stand and step onto a different black mat, which tells us the pressure you feel under your feet. You will be videoed while you are on the black mat to let us see the way you stand and the way you walk. It will take about 1 hour to finish all the tests.

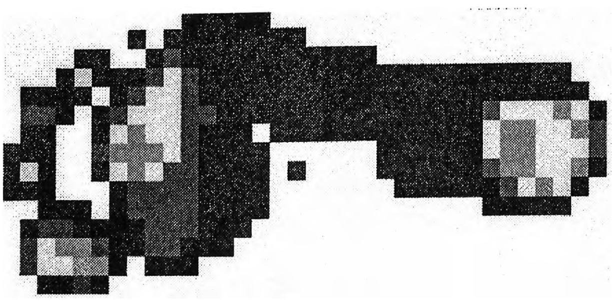
Will there be any problems

- As we only want you to stand still and then to walk, there should be no problems. The tests will not hurt and you have nothing difficult to do.

Do you have any questions?

- If so, ask me.

Please remember you can stop at any time if you want to.



Appendix 3 University of Wollongong
Consent Form

Structure, Pressure and Sensory Foot Function in Children
Annaliese Dowling

This research project is being conducted as part of a Masters of Science (Honours) supervised by Dr Julie Steele in the Department of Biomedical Science at the University of Wollongong.

The researchers conducting this project have in mind the protection at all times of the interests, comfort and safety of the children. The accompanying Parent and Child Information Sheets contain details of the experimental procedures. Your signature below indicates:

1. that you have read the information provided about this project;
2. you have been given the opportunity to discuss the contents with one of the researchers before to commencing the experiment;
3 you understand the procedures;
4. you and your child agree to take part in this project; and
5. your child's participation may stop at any time without jeopardising your involvement with the University of Wollongong, Kidfit or Kinross Wolaroi School or your assessment for any course undertaken through the University, or your treatment at any of these places.

If you would like to discuss the research further please contact Annaliese Dowling (Phone (02) 4221 3881) or Dr Julie Steele (Phone (02) 4221 3881). If you have any questions or comments regarding the conduct of research please contact the Secretary of the University of Wollongong Human Research Ethics Committee (Karen McRae) on (02) 4221 4457.

I agree for my child (name) ________________________________to take part in the study titled "Structure, Pressure and Sensory Foot Function in Children".

Surname:_______________________ Given name:___________________________

Address:____

____

Phone:___________________________ Child's DOB:___________________

Child's Signature:__________________________ Date:________________

Parent/Guardian Signature:_________________________ Date:________________

Name and phone number of contact person in case of emergency:

Name:_____________________________________

Phone:_____________________

University of Wollongong

In reply please quote: DC:KM HE00/049
Further information: Karen McRae PH:42214457

28 September 2000

Ms A. Dowling
Department of Biomedical Science
University of Wollongong

Dear Ms Dowling,

Thank you for your response to the Ethics Committee's requirements for your Human Research Ethics application HE00/049 "Structure, Pressure and Sensory Foot Function in Children".

Your response and amendments meet with the requirements of the Committee and your application was formally approved on 26/09/00.

Yours sincerely,

Karen McRae

Karen McRae
Secretary to the
Human Research Ethics Committee

AUSTRALIA'S UNIVERSITY OF THE YEAR 1999-2000

Appendix 5 Letter from Kidfit

Wollongong's
kidfit
Specialising in the fitness &
weight management of children.

1-2-1 Fitness/ Kidfit
6/19-21 Ralph Black Drive
North Wollongong.
Phone/Fax 42295075

Thursday 21st September, 2000.

Attention: Julie Steele

RE: Permission to use clientele database.

Dear Julie,

I am writing to give Miss Annaliese Dowling permission to use the Kidfit database to assist in gaining subjects for her study titled :
" Structure, Pressure and Sensory Foot Function in Children."
I have supplied Annaliese with a list of children aged 5-12 years of whom she has permission to contact within the Kidfit Studio.
If you require any additional help please feel free to contact me.

Yours Sincerely

Brodie Cambourne B Sc.

(Exercise Physiologist)

Appendix 6 Letter from Kinross Wolaroi Preparatory School

Kinross Wolaroi School

Locked Bag 4
(59-67 Bathurst Road)
ORANGE NSW 2800
Phone: (02) 6392 0300
Fax: (02) 6392 0410
International: Phone +61 2 6392 0300
International: Fax +61 2 6392 0410

29 November, 2000

Head of Department
Biomechanics Research Laboratory
Department of Biomedical Science
University of Wollongong
WOLLONGONG NSW 2522

To Whom It May Concern,

This letter is to confirm that Annaliese Dowling was granted permission to conduct research tests on primary children during Term 4 at Kinross Wolaroi Preparatory School.

Yours sincerely,

Mr A McPhail
Head of Preparatory

Appendix 7 Description of Anthropometric Landmarks

1. **Calf Level:** The level of the maximum circumference of the calf when measured with a steel tape. This level is marked on the posterior surface of the calf. If the maximum circumference occurs at more than one level mark the lowest level.
2. **Ankle Level:** The level of the minimum circumference of the ankle as established when measuring with a steel tape. This level is slightly above the medial and lateral malleoli. The level is marked on the posterior ankle. Always mark the lowest marking for ankle circumference.
3. **Lateral Malleolus:** The level of the most lateral protrusion of the lateral malleolus is marked according to a marking block. If this point occurs more than once calculate the midpoint between these levels to place the marker.
4. **Medial Malleolus:** The level of the most medial protrusion of the medial malleolus is marked according to a marking block. If this point occurs more than once calculate the midpoint between these levels to place the marker.
5. **Minimum Instep Circumference:** The vertical plane of minimum instep circumference when measuring with a steel tape held in a vertical position. This plane is marked on the dorsal, medial and lateral aspects of the foot. The markings are made along the inferior edge of the tape.
6. **Maximum Plantar Arch Height:** The most medial projection of the foot in the minimum instep plane as determined by moving a plain block laterally until its vertical edge contacts the middle instep circumference landmark. A horizontal mark is made at this level. If the most medial projection occurs more than once, mark the lowest level.
7. **1st Metatarsal-Phalangeal Protrusion:** The most medial aspect of the ball of the foot in proximity of the first metatarsal-phalangeal joint as determined with a plain block. If maximum protrusion occurs over a wide surface, the midpoint is selected for marking. The marking is extended over the dorsal surface of the protrusion.

8. **Dorsal Junction of the Foot and Leg:** A horizontal line in the deepest and longest crease of the skin produced over the extensor hallucis longus tendon when the knee is flexed and the ankle dorsiflexed and weight is evenly distributed on both feet, approximately 10 cm apart.
9. **5th Metatarsal-Phalangeal Protrusion:** The most lateral aspect of the ball of the foot in proximity to the fifth metatarsal-phalangeal joint, as determined with a plain block. If maximum protrusion occurs over a wide surface, the midpoint is selected for marking. The marking is extended over the dorsal surface of the protrusion.
10. **Maximum Toe Height:** Any toe other than the hallucis, having the highest phalangeal surface as established with an adjustable block. The point of maximum dorsal protrusion is marked.

(Parham *et al.*, 1992; p 18-19)

Appendix 8 R_1 Values for the Anthropometric Variables

Variable	R_1 value
Height	0.999952
Mass	0.999998
Calf Height	0.9828105
Ankle Height	0.918369
Medial Malleolus Height	0.9644525
Lateral Malleolus Height	0.930356
Bimalleolar Breadth	0.9850125
Heel Breadth	0.9959945
BOF Diagonal Breadth	0.991277
Calf Circumference	0.984509
Ankle Circumference	0.9790785
Heel-Ankle Circumference	0.996574
Instep Circumference	0.991928
BOF Circumference	0.967881
Dorsal Arch Height	0.988297
Plantar Arch Height	0.98103
BOF Height	0.9373955
1st Toe Height	0.922362
Maximum Toe Height	0.8978635
Outside BOF Height	0.921222
Ankle Length	0.992254
Instep Length	0.9887065
BOF length	0.9991185
Foot Length	0.9998745
BOF Breadth Horizontal	0.977969
Outside BOF length	0.9989725
5th Toe Length	0.9994835
1st - 3rd Toes Breadth	0.9604005

Appendix 9 Joint Range of Motion Protocol

Methodology used to measure range of motion of the talocrural joint in the ankle.

Dorsiflexion

1. Position the subject sitting with knee flexed at 30 degrees. The foot is positioned in 0 degrees of inversion and eversion.
2. Stabilise the shank to prevent knee motion and hip rotation.
3. Centre the fulcrum of the goniometer over the lateral aspect of the lateral malleolus.
4. Align the proximal arm with the lateral midline of the fibula, using the head of the fibula as a reference.
5. Align the distal arm parallel to the lateral aspect of the fifth metatarsal.
6. The foot is moved upward, dorsiflexing the foot and ankle complex.

Plantar flexion

1. Position the subject sitting with knee flexed at 30 degrees. The foot is positioned in 0 degrees of inversion and eversion.
2. Stabilise the shank to prevent knee motion and hip rotation.
3. Centre the fulcrum of the goniometer over the lateral aspect of the lateral malleolus.
4. Align the proximal arm with the lateral midline of the fibula, using the head of the fibula as a reference.
5. Align the distal arm parallel to the lateral aspect of the fifth metatarsal.
6. The foot is moved downward, plantar flexing the foot and ankle complex.

(Norkin & White, 1995, p 154-157)

Appendix 10 Summary of Data Collection Schedule

Before Test Day

Information and consent forms handed out prior to test

Test Day

1. Explain procedure and collect consent form, wash and dry feet.

2. Check feet for corns, bunions, calluses.
3. Vibration and pressure measurements to be taken with verbal response to sensation recorded.
4. Measure ankle range of motion and repeat.
5. Mark feet for anthropometric measurements and place stickers on rearfoot.

6. Height and weight measurements to be taken. Repeated three times.

7. Footprints taken using equal weight bearing method. Repeat for each foot.

8. Record rearfoot movement with video, feet together, feet 20 cm apart, and in comfortable position.

9. Record static foot pressure using the emed platform. Repeat twice for each foot.

10. Rearfoot motion recorded with video while walking across the emed platform 5 times for each foot.

11. Twenty-six anthropometric measurements to be taken for each foot and repeated three times.

12. Subject is presented with a Participation Certificate and stickers as a reward.

Certificate of Participation

This Certificate is awarded in appreciation of your participation in the "Structure, Pressure and Sensory Foot Function in Children" study.

Awarded in October 2000

BIOMECHANICS RESEARCH LABORATORY

UNIVERSITY OF WOLLONGONG

Awarded by Annaliese Dowling

Betta Book Binding
M & D Morrisey 4261 2998
26 Fields Street
Kanahooka NSW 2530